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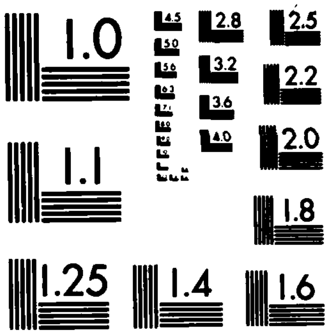

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RAPID RUNWAY REPAIR PROGRAM SUBTASK 1.07 - RAPID CONCRETE CUTTING

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JUNE 1983

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Concrete Cutting	Bomb Damage Repair	
Waterjet	Rock Cutting	
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Two concrete-cutting technologies utilizing high-pressure waterjets have been investigated to assess their feasibility in achieving rapid cutting rates (30 ft^2/min) to facilitate bomb damage repair to runways. The current cutting rate of abrasive waterjets was established as 0.25 ft^2/min for a 60 hp system. Present scaling information indicates that for the near term the technology cannot feasibly achieve the desired cutting rate without a major technical breakthrough. (Continued

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20. ABSTRACT (Continued)

Data from laboratory tests of linear cutting with a single carbide pick assisted with a waterjet indicate that high cutting rates are feasible with that technology. The waterjet-assisted mechanical cutting technology, however, has not been developed as a concrete cutting system. Prototype concepts are proposed in this report and an estimate is made of the power requirement to achieve the desired cutting rate (250 hp to cut 30 ft^2/min).

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PREFACE

This report was prepared by the BDM Corporation, 7915 Jones Branch Drive, Mclean, VA 22102 under contract number F08635-80-C-0206, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, FL.

This report summarizes work done between March 1982 and January 1983. Mr. Edgar F. Alexander was the AFESC/RDCR project officer.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

1. BACKGROUND

The U.S. Air Force Engineering and Services Center (AFESC) is currently performing research and development on methods and procedures for the rapid repair of bomb-damaged runways. Part of this effort includes research and development on concrete-cutting technologies in order to improve upon current methods, which exhibit deficiencies for certain repair approaches.

The nature and extent of the damage to airfield pavements inflicted by nonnuclear munitions varies greatly, depending on the munition size, the type and condition of the pavement, and the existing pavement subbase. Three basic forms of pavement munitions damage have been defined: scabs, small craters, and large craters. This categorization is based on the different repair procedures necessary, recognizing that the demarcation between small and large craters is somewhat arbitrary. These damage classifications are defined as follows.

Scab damage is the gouging of the pavement surface that does not penetrate to the pavement base course. Pavement damage of this category is limited to an area less than 5 square feet.

Small craters have an apparent diameter of less than 15 feet (Reference 1), with damage extending through the concrete surface and into the base course. Pulverized and ejected soil and concrete debris accumulate on the crater's perimeter. Pavement upheaval around the crater edge is likely to occur due to the heaving action of the explosive force.

Large craters are similar to the small craters except the apparent diameter is larger than 15 feet (Reference 1). Again, the crater lip will consist of soil and broken pavement rising 2 to 3 feet above the original pavement surface with concrete fracture and upheaval damage extending 10 to 15 feet beyond the perimeter of the crater.

In conducting bomb damage repair (BDR) numerous activities must be carried out. To expedite the speed of repair, it is desirable to investigate those activities that are slow, presenting a potential bottleneck to the repair, or permit alternative, more effective repair methodologies. Initial research and field testing of established repair procedures have identified deficiencies in current damaged concrete removal capabilities. These deficiencies are discussed in more detail below, but are primarily related to the time required for removal and the potential for additional pavement damage using current techniques.

Bomb damage repair procedures, whether scab or crater, must meet requisite surface roughness and strength criteria to preclude aircraft

damage and provide continuous operational capability. Current and future concepts for airfield repair envision removal of damaged concrete that exceeds maximum upheaval criteria and, possibly, pavement dressing to accommodate precast slab repair concepts.

The present procedures for both small and large crater repairs require that the lip of the crater be leveled and a certain amount of ejecta returned into the crater before backfilling with compacted select fill. In this process, the damaged (fractured and upheaved) pavement surrounding the crater must be removed to conform with the surface roughness criteria. Current concrete-handling techniques utilize a dozer blade, a front loader bucket, or excavator bucket to mechanically break, lift, and remove the damaged concrete from the crater perimeter. Jackhammers are also used in some instances. Although functional, this current procedure has inherent problems.

Equipment must operate from inside the crater to effectively break and remove upheaved and fractured concrete. The shape of some large craters, camouflets, and small craters, may preclude entry or limit equipment maneuverability for concrete cutting.

In these current methods, pavement breaking is uncontrolled because the breaking force focuses inadequate energy to fracture the concrete along predetermined paths. This uncontrolled fracturing propagates unpredictably, damaging otherwise sound pavement beyond the initial bomb damage. This uncontrolled breakage increases crater repair time and requirements and creates unmanageable crater shapes and sizes that further complicate airfield repair activities.

Steel-reinforced concrete cannot be removed with the present techniques. Although recognizing that most USAF airfields do not incorporate reinforced steel concrete design, they do have steel dowels at joints and the presence of reinforcing steel in future runways could render the current technique ineffective.

Current concrete-cutting procedures cannot control the line of fracture. The capability to make clean, controlled cuts with uniform width and depth specifications will permit the dressing of craters to predesignated shape and/or size. For current procedures, this capability would preclude the problem of runouts, extreme slab sizes, and collateral damage repair requirements. For the future, prefabricated bridging structures, precast cap structures, or precast runway sections may become feasible with the capability to execute clean, well-defined cuts.

The purpose of a concrete-cutting system capable of producing very accurate cut alignment lies primarily with the requirements of a precast slab repair method. In the precast slab method an accurate and clean concrete-cutting method to dress the crater to specific dimensions and geometry is needed to execute a rapid repair. If other repair methods that do not require the crater to be dressed to a specific geometry are used, such

as compacted gravel or a polymer concrete, then the use of impact hammers to break the upheaved concrete will aid in the more rapid removal of undesirable and damaged pavement sections.

Recognizing the shortfalls of the existing procedures for concrete cutting in bomb damage repair, AFESC has initiated a series of efforts to enhance these capabilities. The first effort initiated as part of Rapid Runway Repair Program (Contract No. F08635-80-C-0206) was Subtask 1.06 - Concrete Cutting. This subtask included a comprehensive technical review of potential concrete cutting technologies to develop a Recommended Research, Development, Test, and Evaluation Plan for Improved Concrete Cutting (Reference 1). Several of the recommendations from this plan have been implemented in Subtask 1.07 - Rapid Concrete Cutting and Subtask 1.08 - Concrete-Cutting Equipment Evaluation. Subtask 1.08 examined the results of a research and development effort on diamond saws which focused on optimization of diamond saw blade design (Reference 2). Subtask 1.07 examined two high-pressure waterjet-related technologies and is the subject of this technical report.

In addition to the investigations described above which have been conducted by BDM for AFESC, AFESC has been conducting research on a multipurpose excavator which has a concrete-breaking capability based on a shovel and impact hammer attachments. This should ameliorate many of the shortcomings previously cited but cannot provide an accurate controlled-cut needed for a precast slab repair technique.

2. CONCRETE-CUTTING SYSTEM GOALS

In light of the problems associated with existing damaged concrete removal techniques and the desire to retain the precast slab repair method as a viable option, the following concrete-cutting goals have been established (References 1 and 3).

a. A full-depth cutting speed of 30 linear feet per minute in 12-inch thick, 5000 psi compressive strength, portland cement concrete.

b. A cut alignment accuracy of ±1/4 inch in 10 feet.

c. A capability of cutting steel reinforcement.

At the current time, all concrete-cutting technologies fall short of meeting these goals. Because of this, the capabilities of the concrete-cutting system should not only be examined with respect to the goals but should also be compared with the cost, capabilities, and level of development of other cutting systems. At the present, a diamond saw system is the most cost effective, and best-developed, as well as being the fastest and most accurate concrete-cutting method in industry.

3. PROGRAM OBJECTIVES

Most present technologies used for rapidly cutting concrete essentially rely on a single mechanism to cut concrete. For example, the diamond and carbide blade saws rely on an abrasive mechanism, while lasers and burning bars rely solely on thermal energy. These approaches have inherent limitations because they rely on a single physical mechanism to deliver energy into a limited volume of concrete. These limitations may result from limits on material properties, limits on coupling the cutting agent to the concrete structure, or a variety of pragmatic reasons such as size of power supplies or system weights.

The speed of concrete cutting can be related to the energy input from the cutting method. If the cutting technique can be coupled more effectively into the matrix, speed should increase. Subtask 1.07 has investigated two technologies which use high-pressure waterjets to enhance cutting action. These two technologies are (1) a high-pressure waterjet with entrained abrasives and, (2) a waterjet-assisted mechanical cutting system.

The objective of this program is to assess the feasibility of these two technologies to rapidly cut concrete. To conduct this assessment an understanding of key system design and operating parameters is necessary. Because the two technologies to be investigated are at different levels of development, they have different data requirements and, therefore, slightly different research and development objectives. Investigation of each of the two technologies was conducted by a separate principal investigator.

a. Abrasive Waterjet

The investigation of the high-pressure waterjet with entrained abrasive was conducted by the Fluidyne Corporation at Auburn, Washington. This technology is in early stages of development and, thus, requires a relatively comprehensive study of design and operating parameters to determine its feasibility for concrete cutting. The objective of this investigation is to develop the necessary data and understanding to establish:

(1) The current concrete-cutting capability,

(2) Key design and operating parameters, and

(3) A scaling estimate of the equipment to meet AF goals.

The scaling estimate includes equipment size, weight, cost, water requirements and power requirements.

b. Waterjet-Assisted Mechanical Cutting

This technology utilizes a high-pressure waterjet to augment the mechanical cutting action of a carbide-cutting pick or plow. Engineering

and Sciences Technology, Inc., at Golden, Colorado was the principal investigator of this technology. Applications of this technology in mining have provided a body of literature (References 3 and 4) and data on cutting rocks and coal. Because of the availability of this information the investigation was focused on establishing a comparison of cutting performance in concrete with that in rock. The objective of the effort was to develop the necessary data needed to establish:

(1) A baseline concrete-cutting capability,

(2) Key design and operating parameters, and

(3) An estimate of the equipment size and requirements to meet AF concrete-cutting goals.

4. REPORT ORGANIZATION

This Technical Report contains three appendices, in addition to the main body of the report. The main body of the report will summarize and discuss the key topics and results of the investigation and present conclusions and recommendations. Appendix A contains the test plan, which was prepared in June 1982. Appendices B and C contain the detailed technical reports of the respective principal investigators of the abrasive waterjet technology and the waterjet-assisted mechanical cutting technology.

5. REPORT AUTHORITY

This report is published under Air Force Contract Number F08635-80-C-0206, entitled "Task Order Contract for Rapid Runway Repair Program," as part of Subtask 1.07, entitled "Rapid Concrete Cutting."

SECTION II

TECHNICAL REVIEW

1. INTRODUCTION

This section briefly reviews the two hybrid waterjet technologies. This review will include: a brief description of the system components, a discussion of the mechanism of cutting, and identification of key design operating parameters and their impact on cutting performance. The emphasis in this section is to present a general picture of the technologies, while more detailed and quantitative information is contained in subsequent sections and the appendices.

2. ABRASIVE WATERJET

a. System Description

An abrasive waterjet system consists of three major subsystems: (1) a high-pressure water system, (2) an abrasive feed system, and (3) the nozzle system. The equipment used in the work conducted for this Subtask by the Fluidyne Corporation is represented schematically in Figure 1.

(1) High-Pressure Water System. This subsystem of the abrasive waterjet system consists of a pumping system, filters, and high-pressure tubing from the pump to the nozzle. To produce pressures in excess of 30,000 psi, intensifier pumps are required (Reference 1). The tests conducted at Fluidyne's facilities used a 60-horsepower triplex pump capable of producing up to 20,000 psi pressure.

(2) Abrasive Feed System. Abrasive feed systems are of two general types: dry and slurry. The dry abrasive can be fed into the nozzle either by gravity or vacuum generated by the nozzle. A slurry, where the abrasive is suspended in a fluid, can also be pumped under pressure into the nozzle, as well as introduced by gravity or vacuum feed. Most of Fluidyne's work used a dry abrasive feed system utilizing the vacuum produced by the nozzle.

(3) Abrasive Nozzle System. The nozzle is where the abrasive particles are entrained in the waterjet. In developing a nozzle design the goal is to provide a means to efficiently entrain the abrasive in the high-pressure waterjet without adversely affecting the coherence of the jet or presenting intolerable wear to the nozzle. Several alternative nozzle design concepts are discussed in Appendix B and References 1 and 5; however, most of the nozzle configurations currently being investigated have certain general features in common. These nozzles consist of three sections as depicted in Figure 2. The upper section contains an orifice (or orifices) which produces a waterjet. A mixing chamber is the next section. It is here that the abrasive is introduced into the waterjet. The mixing

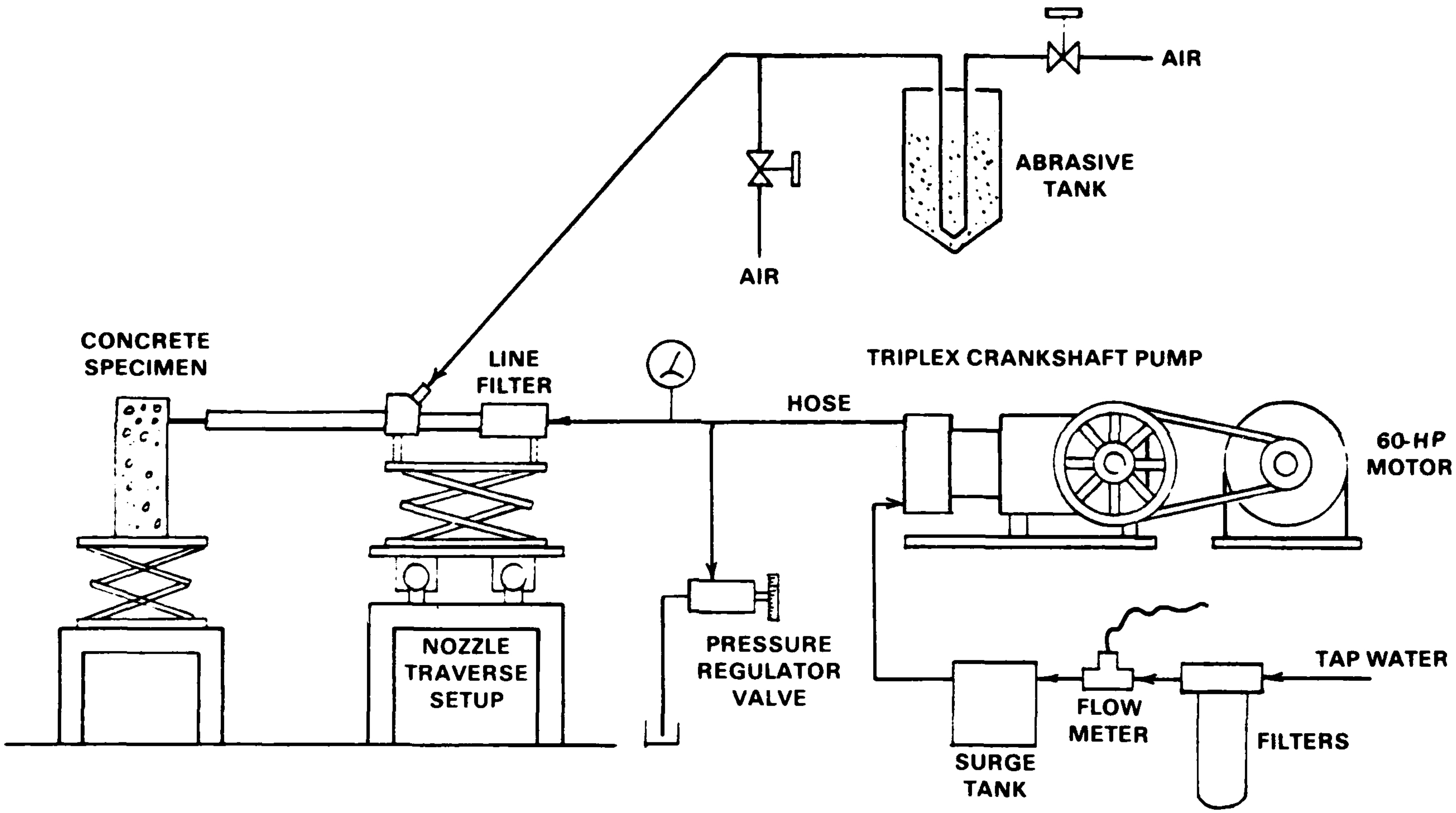


Figure 1. Schematic Illustration of System Components of an Abrasive Waterjet Concrete-Cutting System.

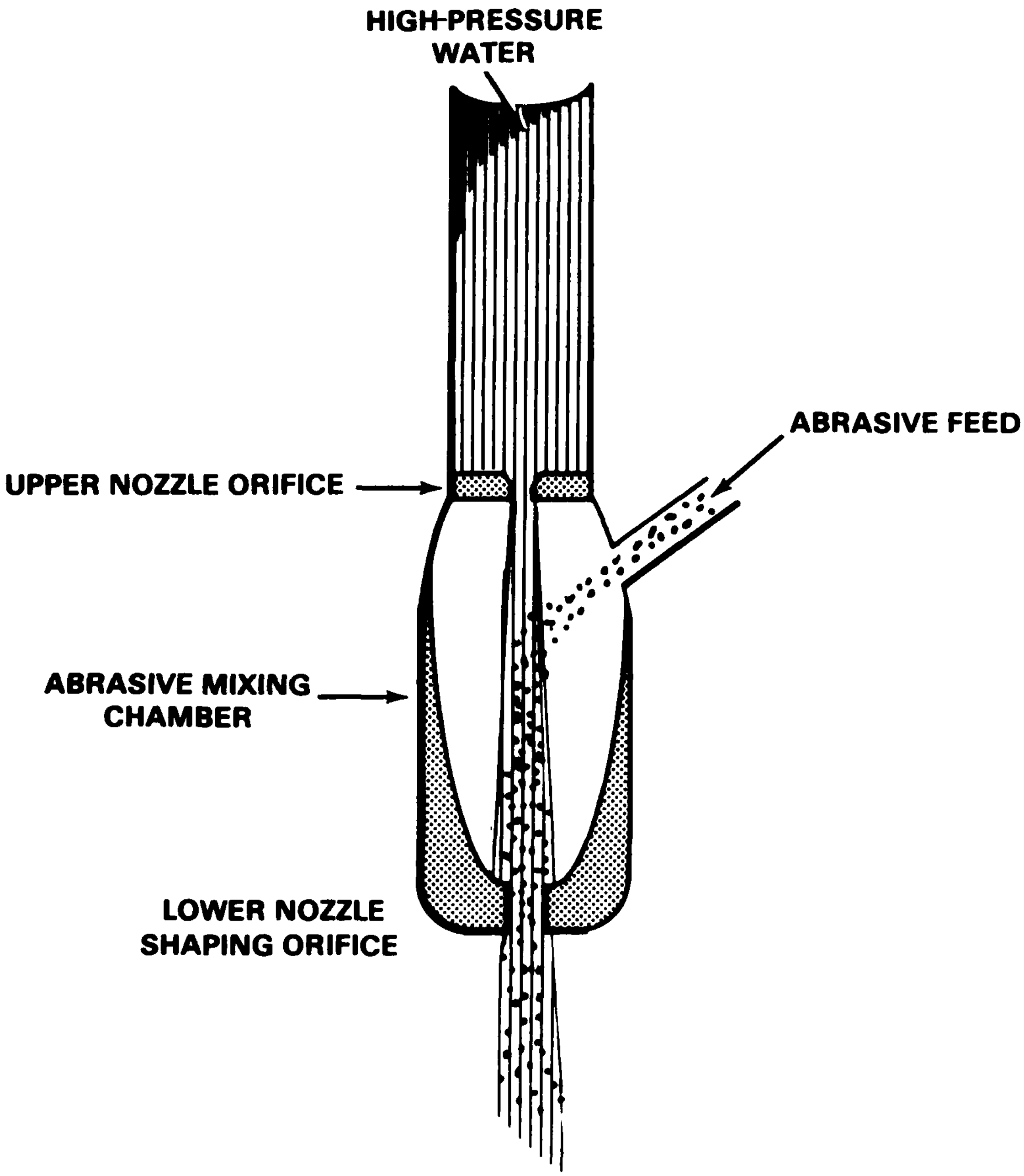


Figure 2. Schematic of an Abrasive Waterjet Nozzle.

action can result from a fluid mixing or from the aspirator action of the waterjet. The final section of the abrasive waterjet nozzle is a second nozzle used to reshape the waterjet,which now contains the abrasives. The performance of the abrasive waterjet depends a great deal on the specifics of the nozzle design such as dimensions, geometry, materials, etc. A more detailed discussion of nozzle design concepts is contained in Appendix B.

b. Mechanism of Cutting

The large concentrated forces of a high-pressure waterjet are sufficient to overcome the structural forces holding together many materials. Obviously,the ability of a waterjet to cut a material depends on the structure and properties of the material itself. A waterjet can more easily cut a soft material or one composed of loosely bonded granules than harder or more tightly bonded materials. This is the reason why pure waterjets have difficulty cutting concrete at pressures less than 30,000 psi, cannot efficiently cut hard aggregates even at much higher pressures, and cannot cut concrete-reinforcing steel.

The introduction of abrasives into the waterjet changes the physics of the cutting process. Now superimposed on the cutting action caused by the localized hydraulic pressure of the waterjet is cutting produced by the abrasive action of the hard abrasive particles. When entrained in the waterjet the abrasive particles have a high velocity and the large momentum of the jet associated with them. These particles are also sufficiently hard and will abrade very hard aggregates and steel reinforcing bars. The cutting action of the abrasive waterjet is to some degree similar to that of a diamond saw blade, with a major difference being the way energy is transmitted to the abrasive particles. For the diamond saw blade the energy is transmitted through the rotation of the steel blade core to the diamonds, while the high-pressure waterjet provides the momentum to entrain abrasives and provide the energy to cut. The quality of cut is better for a diamond saw, primarily due to the physical constraints on the trajectory of the diamonds imposed by the blade matrix and the extreme hardness of the diamonds. Although it is possible to use diamonds in an abrasive waterjet, the cost is prohibitive. Therefore, less expensive abrasives such as garnet are used, although they are not as hard. The quality of cut can be maximized with the abrasive waterjet by maintaining the best jet coherence possible.

The abrasive waterjet can produce a clean cut, several inches in depth, of a quality approaching that of a diamond saw. It can produce deep cuts; however, the quality of the cut depends on the hardness of the concrete aggregate, the abrasive, and the operating parameters. Under conditions where the concrete contains aggregate of a hardness close to that of the abrasive, the quality of cut will decrease more rapidly as the depth of cut increases than if softer aggregate is present. This is because at larger standoff distances the jet is less coherent and will begin to cut around harder aggregate. Figure 3 illustrates this cutting behavior in an 8-inch thick concrete sample containing very hard aggregate.

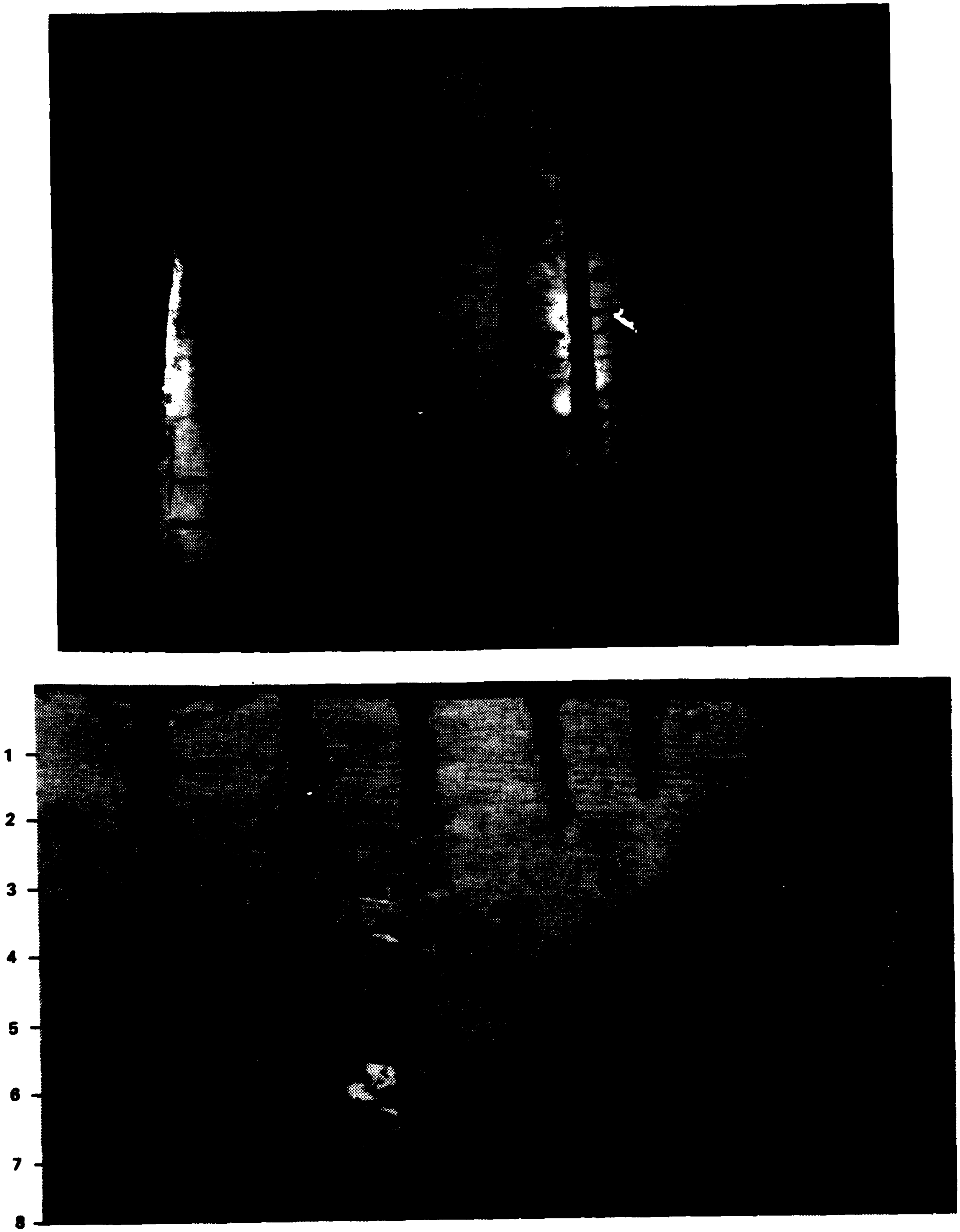


Figure 3. Cuts Made in a Concrete Sample for Varying Number of Passes (8, 6, 4, 3, 3, 2, and 1 Pass From Left to Right).

The abrasive waterjet has capabilities which are not possible for many other concrete-cutting technologies. It is possible to cut curves or any arbitrary pattern with the abrasive waterjet. This technology is also capable of cutting steel reinforcement in concrete although it would be at a slower cutting rate than nonreinforced concrete.

c. Key Operating and Design Parameters

The cutting performance is affected by the energy imparted to each abrasive particle and the number of abrasive particles entrained in the jet. The energy of an abrasive particle can be increased by increasing the velocity of the waterjet which carries it. To increase the velocity of the jet the pressure must be increased. The other factor having a major influence on cutting performance is the number of abrasive particles in the jet. Increasing the number of particles provides more abrasive cutting as long as the density of abrasives entrained in the jet does not appreciably affect the jet velocity.

Changing the abrasive flow rate is not as simple as increasing the water pressure. For a fixed water flow there is a limit to the amount of abrasive which can be introduced. Beyond this saturation density, attempting to introduce more abrasive can adversely affect the coherence of the jet. More abrasive can therefore be introduced into a jet with a larger volume of water flow before this saturation density is reached. The abrasive flow rate is controlled by both the nozzle and the abrasive feed system. The nozzle design can limit the volume of abrasive which can be introduced into the jet through any of the following: the size of abrasive intake port, the dimensions of the mixing chamber, and the vacuum produced by the nozzle to entrain the abrasive. The abrasive feed system also determines the abrasive feed rate. For the dry feed system used by Fluidyne, the feed rate could be controlled through the use of different size orifices in the abrasive feed line.

As the above discussion indicates and as the early experimental results support, the most critical impact on cutting performance is made by the nozzle design. It must efficiently entrain as large a volume of abrasive as possible and still retain jet coherence to maximize cutting performance. Modifications in the nozzle design can have substantial effects on performance.

The effect on cutting performance by the operating parameters such as pump horsepower, system pressure, water flow rate, and abrasive flow rate are all interrelated to each other and to the nozzle design, as discussed above. This made it difficult to rank the relative importance of these parameters on total cutting performance. However, these operating parameters have a greater impact on performance than others including: traverse speed, abrasive size, standoff distance, and angle of impingement.

Fluidyne used a 60-horsepower pump in all of its laboratory tests and, therefore, information on the effect of pump horsepower on a single

nozzle is not available. Information available from the literature on work done by other investigators using different size pumps is of little value because of differences in nozzle designs. As an estimate, a linear scaling is assumed regarding power and cutting performance. This will be discussed in more detail in subsequent sections.

The power of an abrasive waterjet is approximately proportional to the product of the pressure and mass flow rate (Power $\propto$ Pressure x Mass Flow Rate). (In cases where the mass flow rate of the abrasive is small with respect to that of water, then the mass flow rate can be replaced by water flow rate in this expression.) Laboratory tests were conducted by Fluidyne on the effects of varying pressure and flow rate for a fixed pump horsepower and a fixed abrasive feed rate. The results indicated that cutting performance increased with increased pressure under these constraints.

Tests were also conducted on the effect on performance of increasing the abrasive flow rate for a fixed pressure and water flow rate. The cutting rate increases as the abrasive feed increases. The rate of improvement diminishes as the jet becomes more laden with abrasive.

The results of the experimental tests led to an interesting question which should be addressed in system optimization. This is whether a better cutting rate can be achieved for a fixed horsepower by increasing the system pressure or increasing the water flow rate which would, in turn, allow a higher abrasive feed rate.

The major abrasive waterjet system parameters have been discussed qualitatively in this Section. Section III presents a more quantitative description of the major test results.

3. WATERJET-ASSISTED MECHANICAL CUTTING

The work conducted on the waterjet-assisted mechanical cutting technology made use of a laboratory test apparatus to provide data on a single cutting pick and waterjet making linear cuts in a concrete test slab. A detailed description of the test apparatus and instrumentation is contained in Appendices A and C. In a cutting system utilizing this technology, it is envisioned that a cutting wheel will be composed of an array of picks and waterjets.

a. System Description

A schematic of the laboratory test setup is shown in Figure 4. The concrete sample was driven under the carbide pick by a hydraulic ram. As the pick penetrated the concrete the horizontal, vertical, and side forces were monitored and recorded. Figure 5 is a photograph of the system. The system components needed in a cutting system are the carbide pick and the waterjet system.

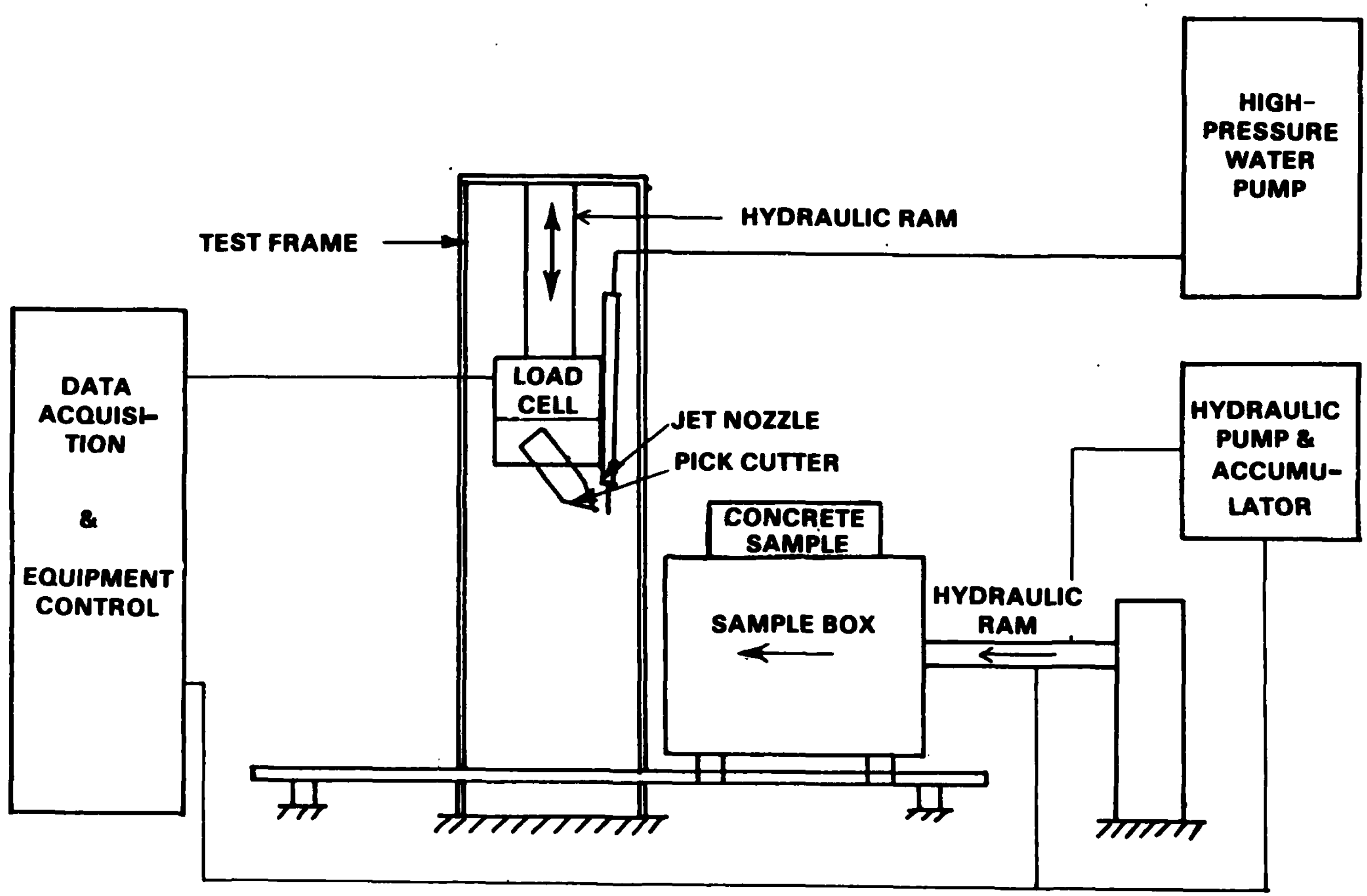


Figure 4. Equipment and Instrumentation Schematics.

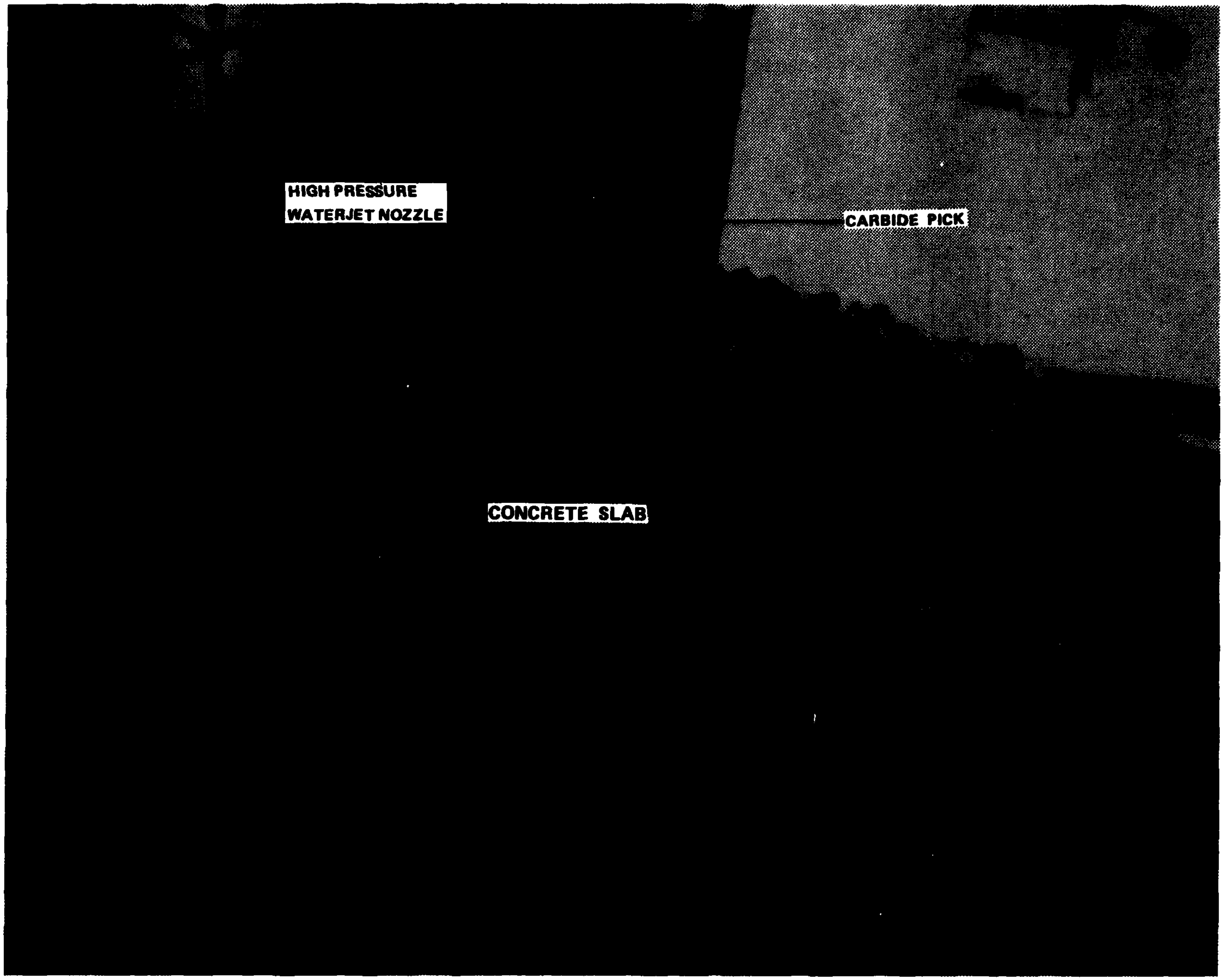


Figure 5. Waterjet-Assisted Mechanical Cutting Experimental Setup.

(1) Carbide Pick. A carbide pick is shown in Figure 6. The pick has a tungsten carbide tip. These picks are mounted in cutting systems so that they are free to rotate about their longitudal axis, providing a self-sharpening action. The price of a carbide pick is approximately 2 dollars. The depth of penetration in the concrete could be varied for the laboratory tests at either 0.5 or 0.75 inch.

(2) Waterjet System. The high-pressure waterjet system used for these laboratory tests used a small 30-horsepower pump to produce a 10,000 psi jet of approximately 17 horsepower.

b. Mechanism of Cutting

The waterjet-assisted mechanical cutting system uses a high-pressure waterjet to augment the cutting action of a tungsten carbide pick. As a cutting pick is driven into the concrete it fractures the concrete, producing the cutting action. Cracks propagate ahead of the pick as it traverses through the concrete. When a high-pressure waterjet is directed in front of the pick it enters these cracks, acting as a hydrofracturing mechanism to assist the mechanical fragmentation process, thus reducing the mechanical forces required to cut the concrete. The waterjet itself is not cutting in the same manner as it would alone, but it assists in exploiting cracks to fragment the concrete and lubricates the mechanical bit. The operating pressure of the waterjet can be substantially lower than that needed for cutting with the waterjet alone.

Because both the waterjet-assisted mechanical cutting system and carbide saws utilize the same type of cutting pick, a brief discussion of their differences is in order. As described above, the cutting action of the waterjet-assisted mechanical cutting utilizes a controlled localized fracturing of the concrete. For such a system the velocity of the tip of the pick is approximately 100 to 200 ft/min with each pick taking a "bite" into the concrete of 0.25 to 1.0 inch. This is in contrast to the cutting action of the carbide saw which cuts by an abrading action of the carbide picks against the concrete. For the carbide saw the velocity of the tip of the picks is as fast as 2,500 ft/min, and each pick just barely scores the concrete. The difference in the cutting mechanisms can cause appreciably more wear on the carbide picks in the carbide saw than the waterjet-assisted mechanical cutting approach. The difference also allows for much larger cutting rates for the waterjet-assisted cutting system.

The quality of cut for the waterjet-assisted mechanical cutting system is not as good as that produced by a carbide saw, abrasive waterjet, or diamond saw. This is because the cutting mechanism relies on localized fracturing and will not produce as clean and smooth a cutting face as the other technologies. Although the cut face may be rough, the waterjet-assisted mechanical cutting technology should still be capable of an accurate cut alignment.

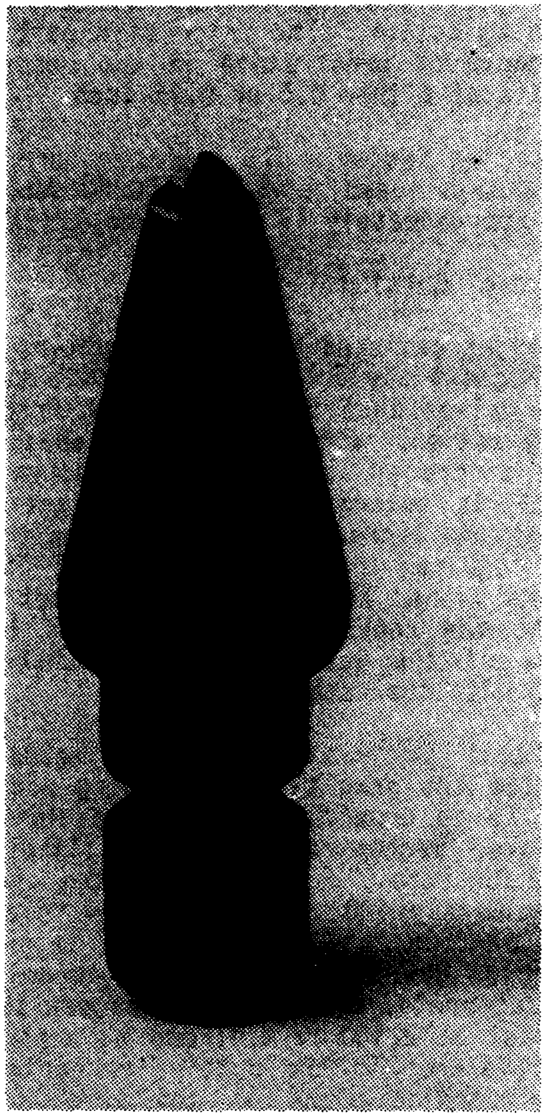


Figure 6. Tungsten Carbide Cutting Pick.

c. Key Operating and Design Parameters

Because the major emphasis of the test was to establish sufficient data to validate the use of concepts and information already used in mining applications of the technology, only a few parameters were varied. A more detailed discussion of how the linear cutting tests relate to a prototype cutting system is given in Section IV and Appendix C.

The major operating parameters are the type of cut, presence and absence of the waterjet, depth of penetration of the cutting pick, and the linear traverse rate.

(1) Type of Cut. In Figure 7, different types of cuts are illustrated in a cross-sectional schematic of a concrete slab. The forces on the cutting pick vary substantially from one type of cut to another. The forces for a zero relief cut are greater than those for a one-side cut which are in turn greater than a two-side cut. In a concrete-cutting system, the one-side cut would most closely approximate the forces on a cutting wheel (Section IV and Appendix C) where the picks are set like teeth on a saw blade.

(2) Presence of the Waterjet. Linear cutting tests were made both "dry" and with the presence of the waterjet. The effect of the waterjet in reducing the forces on the cutting pick also depends on the type of cut. For the zero relief cut a modest or negligible reduction in forces was observed. However, for the one-side cut the use of the waterjet produced an appreciable reduction in forces, as much as 60 percent. The tests were conducted using a waterjet at approximately 10,000 psi pressure.

(3) Depth of Penetration. The depth of penetration of the pick affects the cutting forces. The dimensions of the pick limit the maximum depth of penetration. For dry cutting, the forces increase with increased depth of cut. When the waterjet is used to assist the cutting, it is not necessarily true that the cutting forces increase with depth of cut. The reason for this is that at certain penetration depths, the cracks which are propagated in front of the pick are more readily affected by the high-pressure waterjet. This phenomenon has been observed for sandstone, as well as concrete.

(4) Linear Traverse Rate. In the experimental tests, the concrete slab was driven under the cutting pick by a hydraulic ram. The ram could produce two different traverse velocities - 100 ft/min and 160 ft/min. For these two velocities there was no consistent trend indicating higher cutting force required for the one speed than the other.

The discussion of the operating and design parameters in this section gives a qualitative indication of their effects on the cutting forces observed in the lab tests and thus the potential effects on cutting performance. More detailed quantitative discussions are given in the following section and Appendix C.

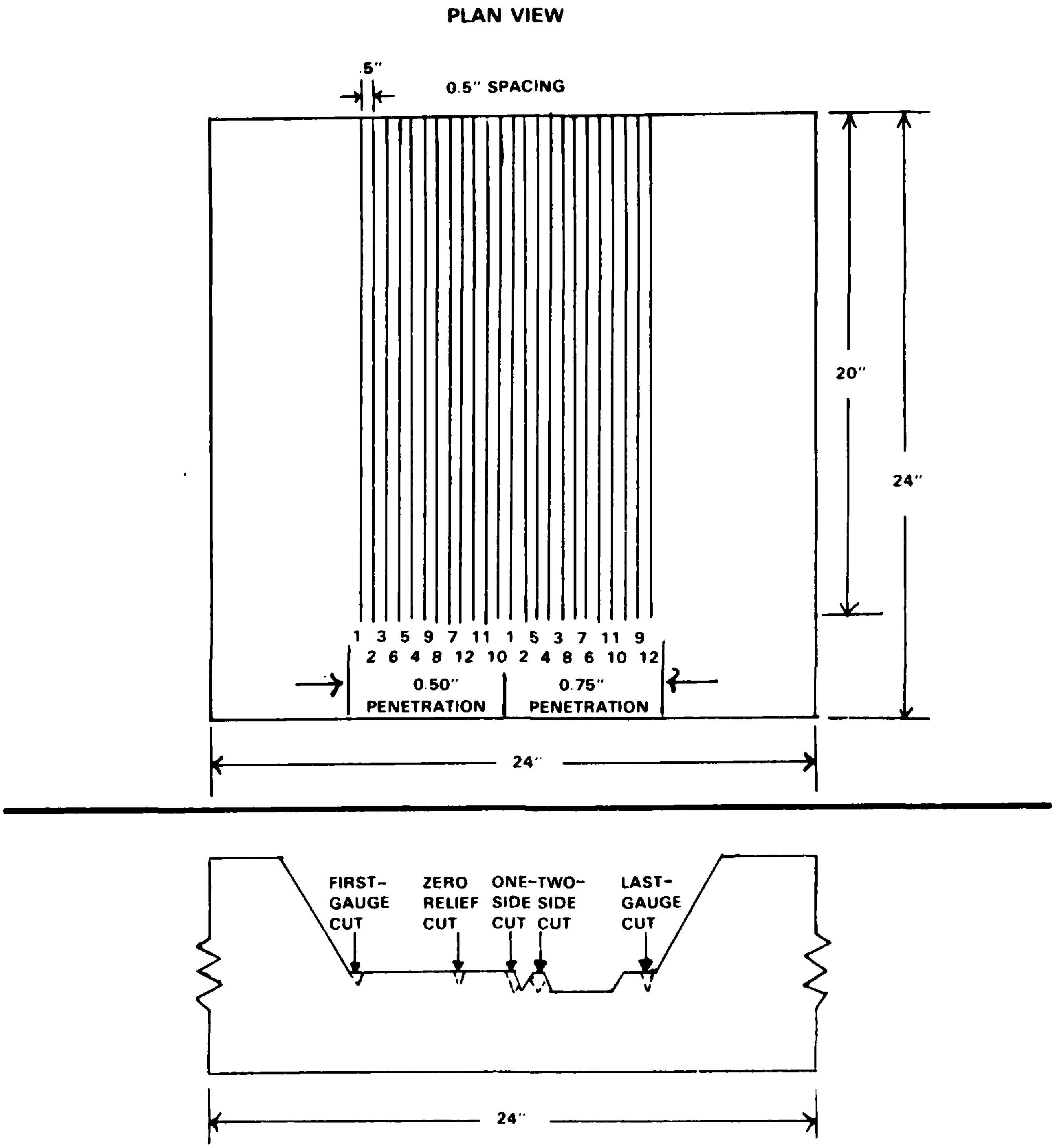


Figure 7. Test Pattern Indicating Different Types of Cuts.

SECTION III

SUMMARY OF TESTS AND RESULTS

1. INTRODUCTION

This section will provide a summary of the laboratory tests conducted for this subtask and the major results. Detailed information regarding the test approach, methods, and results is contained in the appendices. Differences in the tests conducted according to the test plan (Appendix A) are discussed in this section. The test results will be briefly discussed in regard to other investigators and other concrete-cutting technologies.

2. ABRASIVE WATERJET

Because this is an immature technology the test approach was oriented toward obtaining basic data to assess the potential of the technology. To this end, certain areas were not investigated as originally intended in the test plan. The tests which were conducted focused on those areas felt to have the greatest ultimate impact on the cutting performance and to provide most fundamental understanding of the technology. Results were obtained on the effect of several parameters on cutting performance.

The following areas were investigated in the tests conducted by Fluidyne:

a. Assorted nozzle designs,

b. Abrasive feed systems,

(1) Abrasive size and type

(2) Abrasive feed rate

c. Water pressure,

d. Water flow rate,

e. Traverse speed,

f. Angle of impingement

g. Number of passes, and

h. Standoff distance.

Early in the experimental testing it was realized that the most significant impact on the cutting performance lies in the nozzle design. A variety of nozzle designs were therefore tested. A discussion of nozzle

design concepts is contained in Appendix B. In addition to identifying the nozzle design as the most critical factor influencing cutting performance, early tests also indicated the advantages of a dry abrasive feed system over slurry systems. A dry abrasive feed system shows a greater flexibility in handling different sized abrasives. Larger abrasive particle sizes are more difficult to suspend in a liquid, causing difficulties in slurry systems. The dry abrasive feed system also appears to more efficiently entrain a larger volume of abrasives in the waterjet; however, this efficiency is also greatly affected by the nozzle design.

Table 1 summarizes the qualitative results of tests involving the above parameters. The discussion below will focus on the cutting capability which has been established in the tests and the effects of abrasive feed rate, water pressure, flow rate, and number of passes. The other parameters are addressed in Appendix B.

a. Established Cutting Performance. A number of corporations have been involved in abrasive waterjet research, encompassing a variety of different approaches, operating parameters, and applications (References 5 to 9). The cutting performances reported in the references for Flow Industries and BHRA, along with test results from Fluidyne's work in this program, are listed in Table 2. There are several important aspects to these results. First, all of the cutting rates are within an order of magnitude of each other, although the operating parameters, nozzle designs, and concretes differ. This brackets a range on cutting capabilities for the technology as a whole. The next point is that even the best cutting rate, Fluidyne's 0.25 ft^2/minute, is far short of the Air Force goal of 30 ft^2/minute. Finally, even with limited data, there seems to be little correlation between the operating parameters of these different systems and the cutting performance, implying that the nozzle design (or less possibly the concrete type) is a major parameter.

The cutting rate achieved by Fluidyne's abrasive waterjet should be used as a benchmark for comparisons with other concrete cutting technologies. The test parameters are well documented in Appendix B and in addition the tests were conducted in a standard concrete which has also been used in diamond saw testing and testing of the waterjet-assisted mechanical cutting technology.

b. Abrasive Feed Rate. This parameter has a major impact on the cutting rate. Figure 8 shows the effect on depth of cut, which is proportional to the cutting rate for a fixed traverse speed.

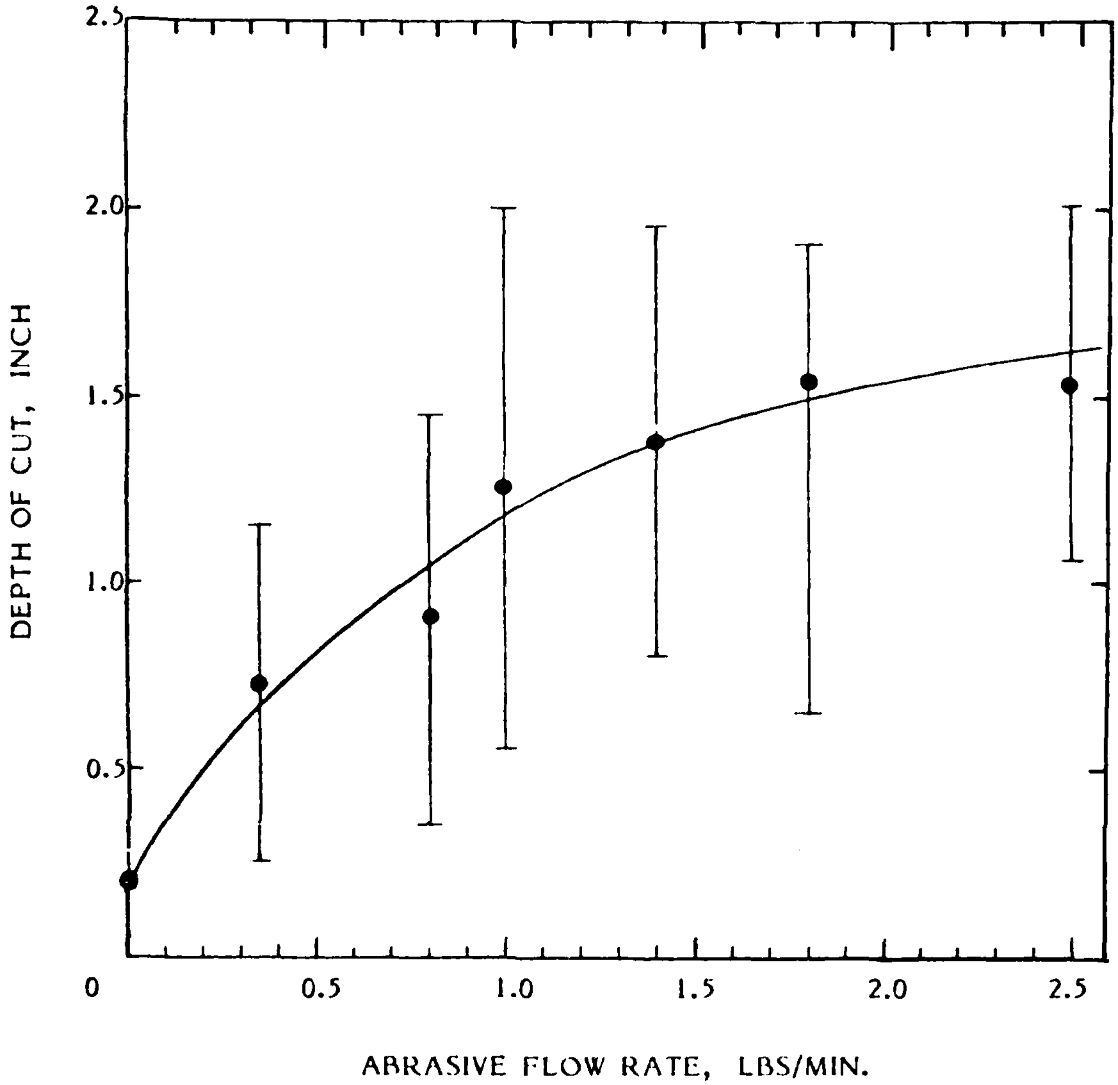
c. Water Pressure/Water Flow Rate. For a given pumping power the waterjet pressure and flow rate are related (Power $\propto$ Pressure x Mass Flow Rate), thus if one is increased the other is decreased. If the other operating parameters are held constant (in particular, the abrasive feed rate) then the cutting rate will increase with increasing pressure and decreasing flow rate at constant pump horsepower. This is shown in Figure 9. This range of pressures (12, 15, and 17 ksi) differs from that which was stated

TABLE 1. SUMMARY OF EXPERIMENTAL RESULTS.

PARAMETER	HOW VARIED (APPROXIMATE RANGE)	EFFECT ON CUTTING PERFORMANCE
PRESSURE	INCREASED AT CONSTANT PUMP HORSEPOWER (11,000-17,000 PSI)	CUTTING RATE INCREASES. HAS A MORE SIGNIFICANT EFFECT FOR HIGHER TRAVERSE SPEEDS AND ON HARDER AGGREGATE.
ABRASIVE FEED RATE	INCREASED (0-2.5 lb/min.)	CUTTING RATE INCREASES RAPIDLY INITIALLY THEN LEVELS OFF.
ABRASIVE	INCREASED SIZE (100-60-30 MESH)	INCREASED CUTTING RATE, PARTICULARLY AT HIGHER FEED RATES.
	TYPE (GARNET/SILICON CARBIDE)	NO MAJOR EFFECT.
TRAVERSE SPEED	INCREASED (0.5-2.5 ft/min.)	DEPTH OF CUT DECREASES RAPIDLY THEN MORE SLOWLY. THE CUTTING RATE (DEPTH × TRAVERSE) REMAINS FAIRLY CONSTANT ±20%
STANDOFF DISTANCE	INCREASED (0.2-1.2-22 IN.)	CUTTING RATE DECREASES VERY SLOWLY (NO APPRECIABLE EFFECT UP TO 10 IN.)
NUMBER OF PASSES	INCREASED	DEPTH OF CUT INCREASES, WITH EACH SUCCESSIVE PASS SLIGHTLY LESS EFFECTIVE. QUALITY OF CUT DECREASES
ANGLE OF IMPINGEMENT	TRAILING (0-45° OFF NORMAL)	BETTER QUALITY CUT, MORE UNIFORM DEPTH THAN NORMAL INCIDENCE.
	LEADING (0-45° OFF NORMAL)	MORE RAGGED CUT THAN NORMAL INCIDENCE. AT ALL ANGLES AVERAGE DEPTH OF CUT APPROXIMATELY CONSTANT.
CONCRETE AGGREGATE	STONE MOUNTAIN GRANITE STEILACOOM IGNEOUS ROCK	CUTTING IN CONCRETE CONTAINING GRANITE APPROXIMATELY TWO TIMES FASTER WITH ENHANCED QUALITY.

TABLE 2. CURRENT CONCRETE CUTTING CAPABILITIES - SINGLE-NOZZLE SYSTEMS.

COMPANY	CONCRETE AGGREGATE	PUMP HORSEPOWER	PRESSURE (KSI)	FLOW (GPM)	ABRASIVE FEED (LB/MIN)	CUTTING RATE (FT^2/MIN)
FLUIDYNE	GRANITE	60	15	6	2-3	0.25
FLOW	NOT SPEC.	44	30	3	4	0.08
BHRA	NOT SPEC.	>80	10	10-15	16	0.03



TEST SPECIMEN Cast Concrete	TEST DATE 9-14-82
ORIFICE CONE 5-Parallel-Jet	ORIFICE SIZE 22 mils
WATER PRESSURE 15,000 PSI	FLOW RATE 5.5 - 6.0 GPM
ABRASIVE TYPE Garnet Grid #36	FEED RATE LBS/MIN.
TRAVERSE SPEED 2.0 feet/min.	NOZZLE STANDOFF 0.5 INCH
JET ANGLE 90°	NO. OF PASSES 2

Figure 8. Depth of Cut vs. Abrasive Flow Rate.

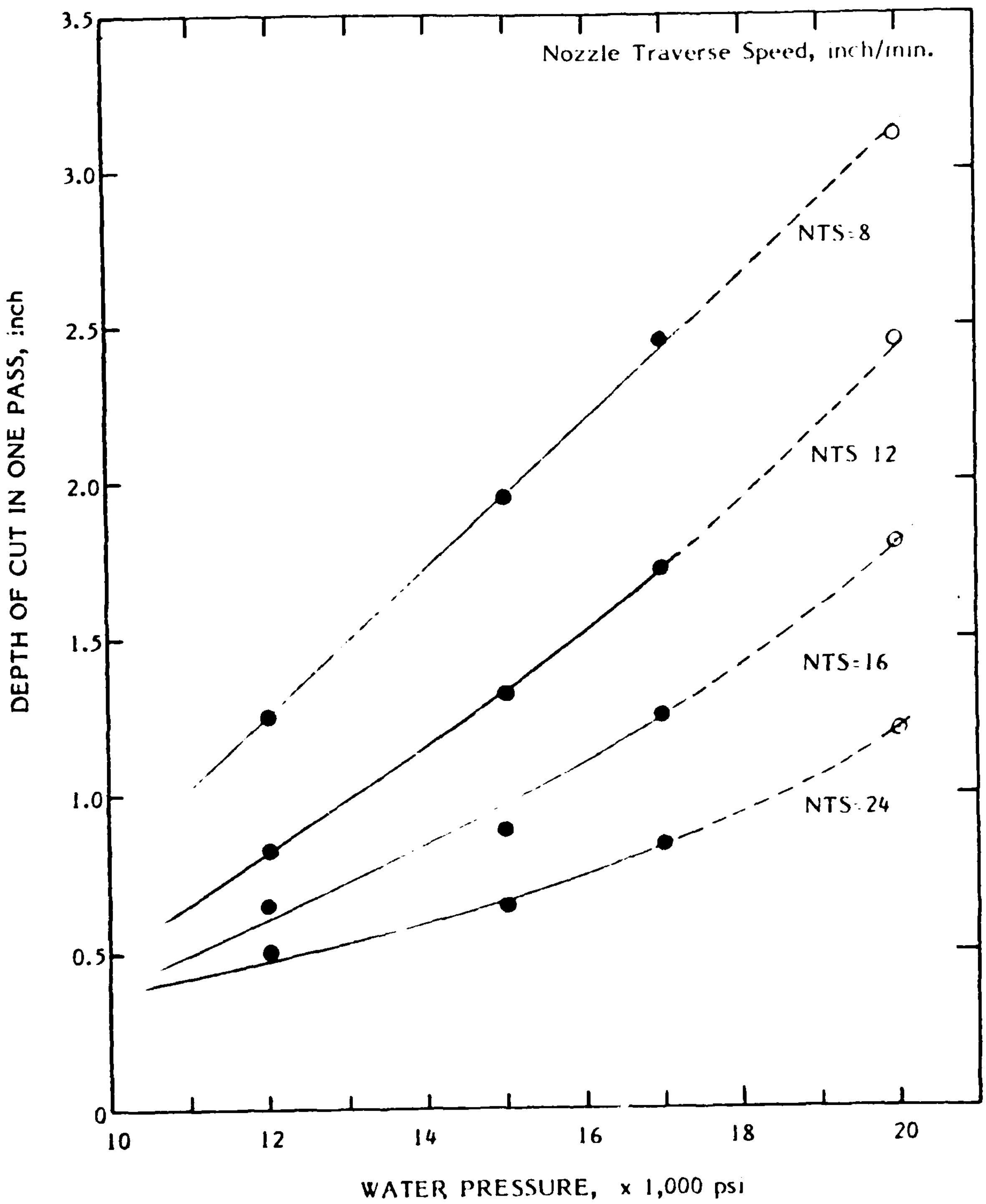


Figure 9. Depth of Cut as a Function of Pressure for Constant Pump Horsepower.

in the test plan (10, 15, 20 ksi). These pressures were determined by both pump characteristics and the size of orifices in the nozzles.

Originally, the test plan provided for experiments at various pumping power levels. To achieve this with a single pump, part of the high-pressure water from the pump must be bled off; unfortunately, this process could not be accurately controlled to provide reproducible results. Because of this problem, the tests were redirected to obtain more information on other parameters such as the effect of abrasive type and grain size (Appendix B) which were not originally included in the test plan.

d. Number of Passes and Exposure Time. Although the data were not available on the effect of varying power for a single nozzle, data were developed for cutting performance (depth of cut) for multiple passes of the abrasive jet. This is approximately equivalent to passing a manifold of multiple nozzles over the concrete with each nozzle requiring 60 horsepower. This information, along with the diameter of the abrasive waterjet and the traverse rate, can be used to plot the depth of cut for a given exposure time of the abrasive waterjet (Figure 10). The exposure time is defined below.

$$\text{Exposure time} = \frac{n \times d}{v}$$

where n = number of passes

d = diameter of the jet

v = traverse velocity

Figure 10 can be used to estimate the number of passes of the nozzle (or nozzles in a multiple-nozzle system) to achieve a particular depth of cut and traverse speed. For a multiple-nozzle system an estimate of the pump horsepower can be obtained by multiplying the number of nozzles by 60 horsepower. This scaling is valid only for cutting concrete of the same composition (mountain stone granite aggregate) and same nozzle operating parameters.

3. WATERJET-ASSISTED MECHANICAL CUTTING

The test equipment, procedures, and results are discussed in detail in Appendix C. Briefly the test approach was as follows. Waterjet kerfing tests were conducted on concrete specimens over a range of pressures suitable for waterjet-assisted mechanical cutting, to determine the cutting action that is attributable to the waterjet alone. Cutting tests were conducted using a carbide cutting pick alone and with waterjet assistance. The forces on the cutting pick were monitored to determine the effect of the waterjet when making different kinds of cuts. Figure 7 illustrated the

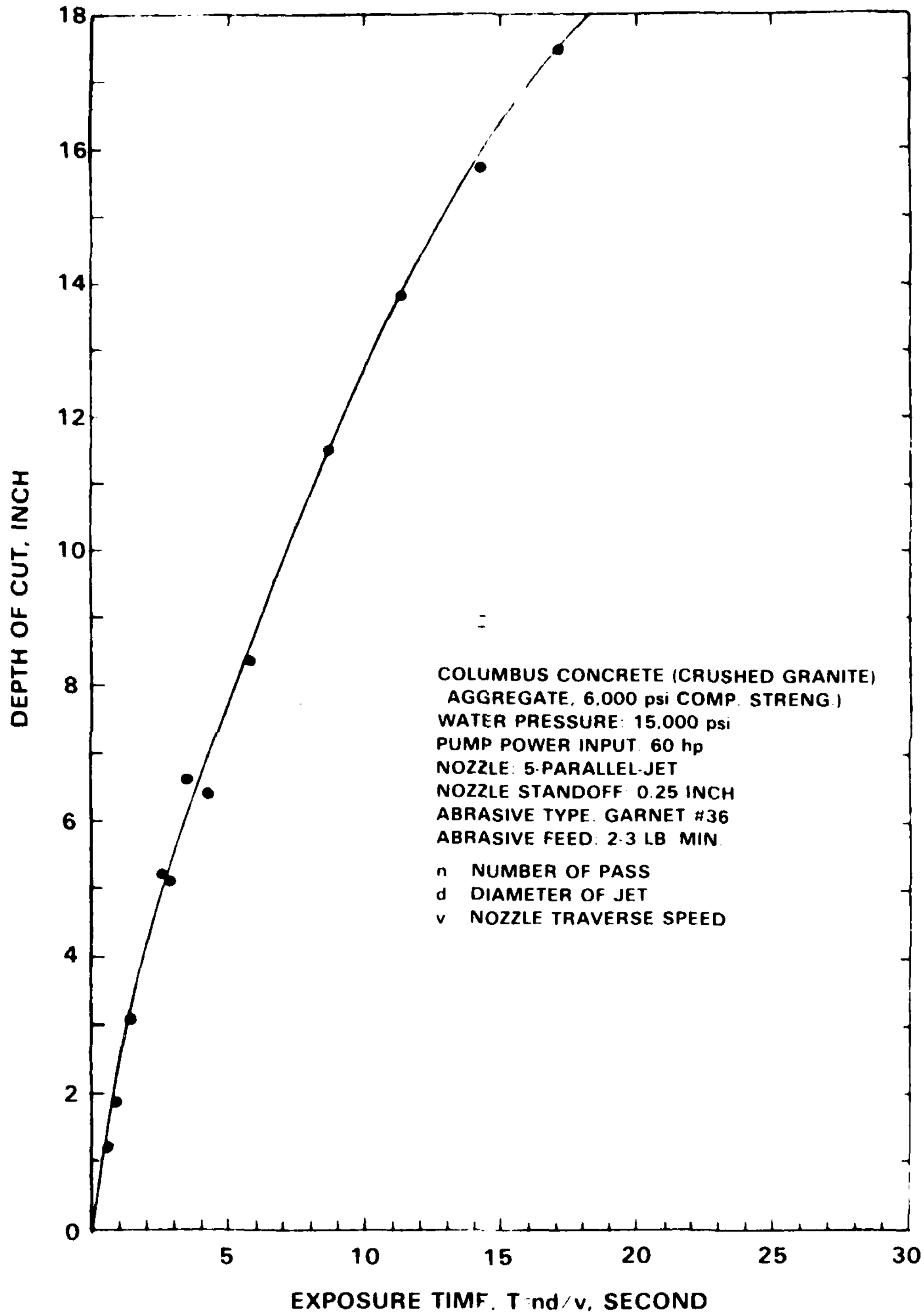


Figure 10. Depth of Cut vs. Exposure Time.

different kind of linear cuts as viewed through a cross section of a concrete slab. The major results of these cutting tests are discussed below.

a. Waterjet Kerfing. A high-pressure waterjet with varying pressures (5,000, 10,000, and 20,000 psi) and nozzle diameters (0.016 and 0.024 inch) produced a maximum depth of cut of approximately 0.13 inches at a traverse rate of 75 ft/min. For the operating parameters (10,000 psi and 0.025-inch diameter nozzle) used in conjunction with the carbide cutting pick, the waterjet alone produced a deepest cut of 0.003 inches at a 75 ft/minute traverse rate, essentially a negligible effect.

b. Mechanical Cutting With and Without the Waterjet. Data were gathered on the vertical (thrust), horizontal (drag), and side forces experienced by the cutting pick in a large number of both "dry" and waterjet-assisted cuts. The data have been categorized and plotted according to type of cut, penetration depth, traverse rate, and spacing between adjacent cuts in Appendix C. The results are ambiguous to predict trends in cutting force as a function of penetration, spacing, or traverse rate. However, the use of the waterjet generally reduced the cutting forces for the one-sided cuts and had a small or negligible effect on the zero relief cuts. Figures 11 to 16 show the average forces (vertical, horizontal, and side) plotted versus penetration depth for "wet" and "dry" cuts (one-side and zero relief cuts). The reduction of forces with the use of the waterjet for one-side relief cuts is approximately 30 to 50 percent for vertical forces, 20 to 40 percent for horizontal forces, and 60 percent for side forces.

The data on cutting forces can be used to estimate power requirements for a system to achieve the Air Force cutting goals. This will be addressed later.

c. Cutting Rates. The linear cutting tests indicated that a single tungsten carbide cutting pick could make a 0.50- to 0.75-inch deep cut at a rate of 100 to 160 ft/minute. This is equivalent to cutting rates (depth x traverse rate) of 4.2 to 10.0 ft^2/minute requiring approximately 3.4 horsepower from the hydraulic ram. Limitations on the experimental apparatus precluded attempting higher cutting rates. To serve as a reference, the cutting rates which are currently obtained by state-of-the-art diamond saw blades are approximately 4.0 ft^2/minute. In comparison the waterjet-assisted mechanical cutting method looks quite good; however the linear cutting action of the pick has to be efficiently incorporated into a cutting system. The next section will address such potential concepts.

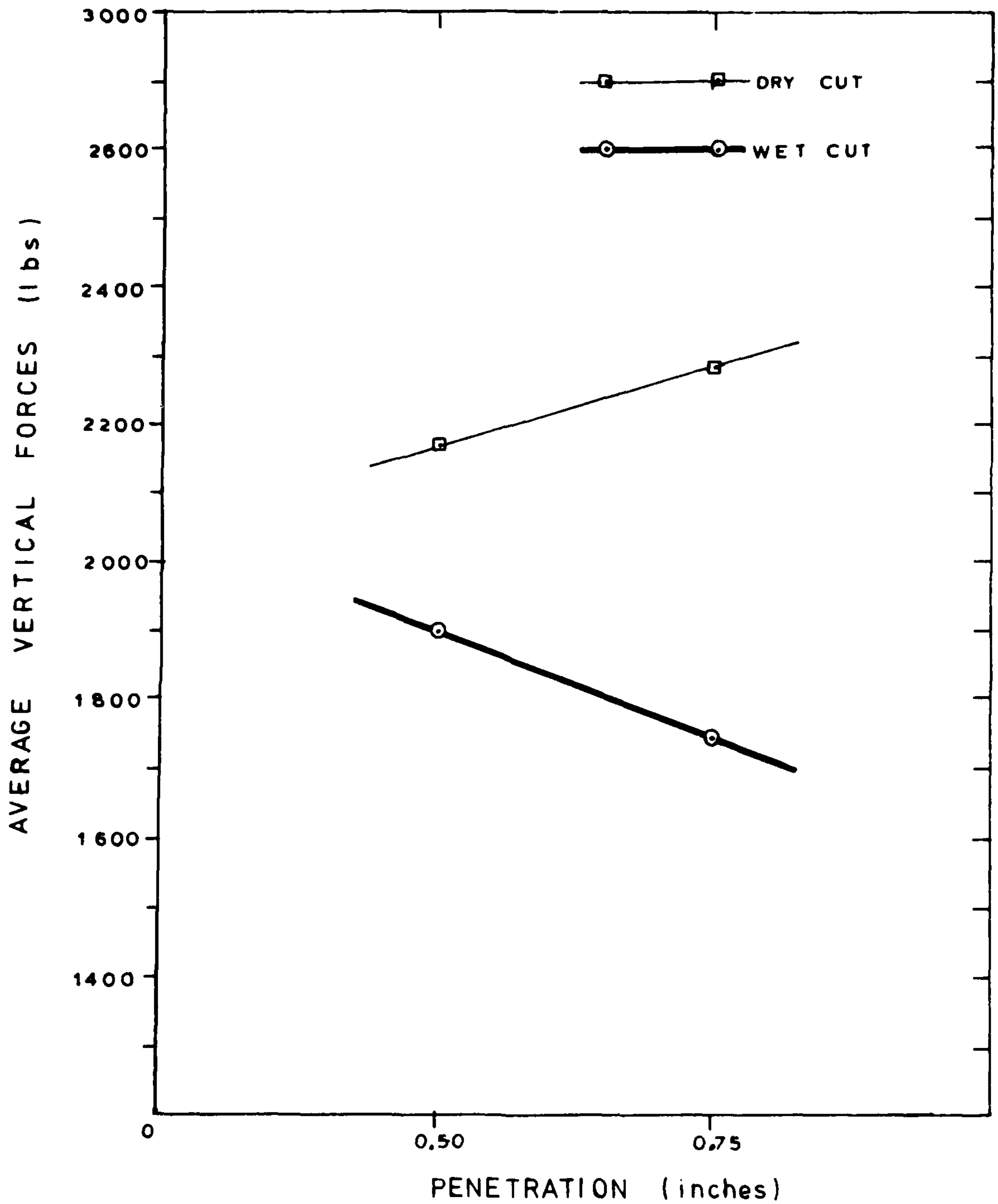


Figure 11. Average Vertical Forces vs. Penetration Depth For One-Side Cut.

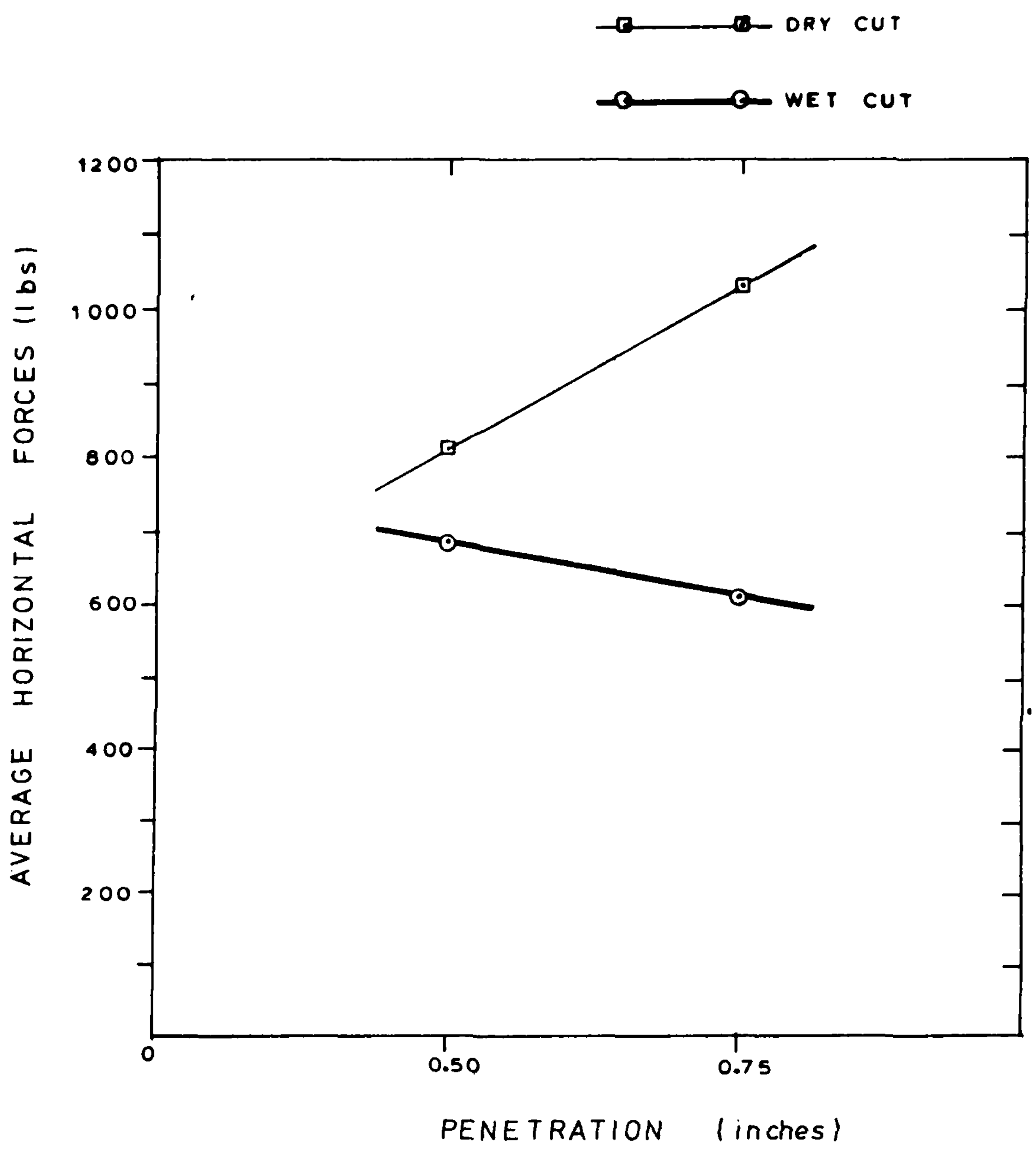


Figure 12. Average Horizontal Forces vs. Penetration Depth For One-Side Cut.

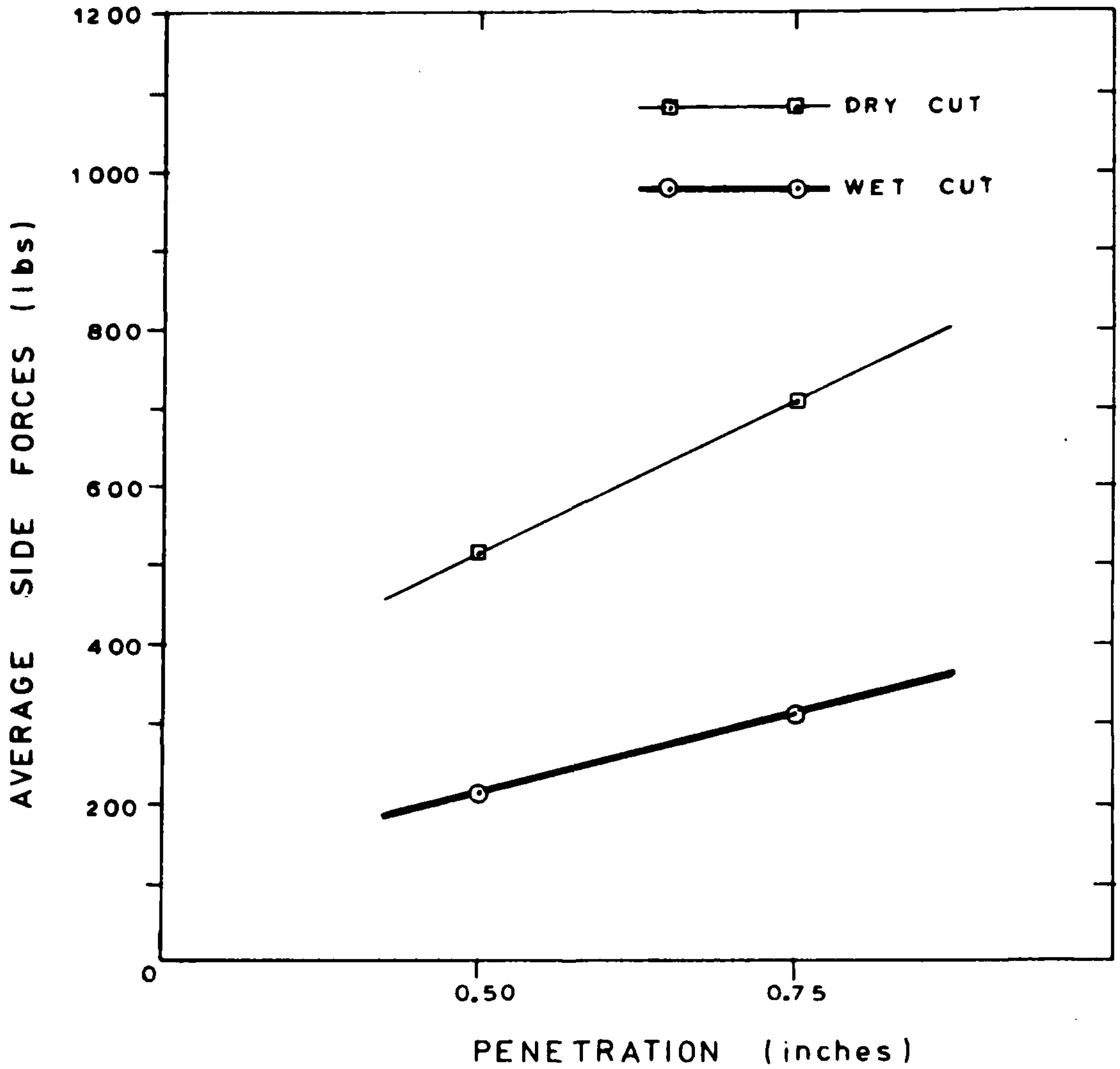


Figure 13. Average Side Forces vs. Penetration Depth For One-Side Cut.

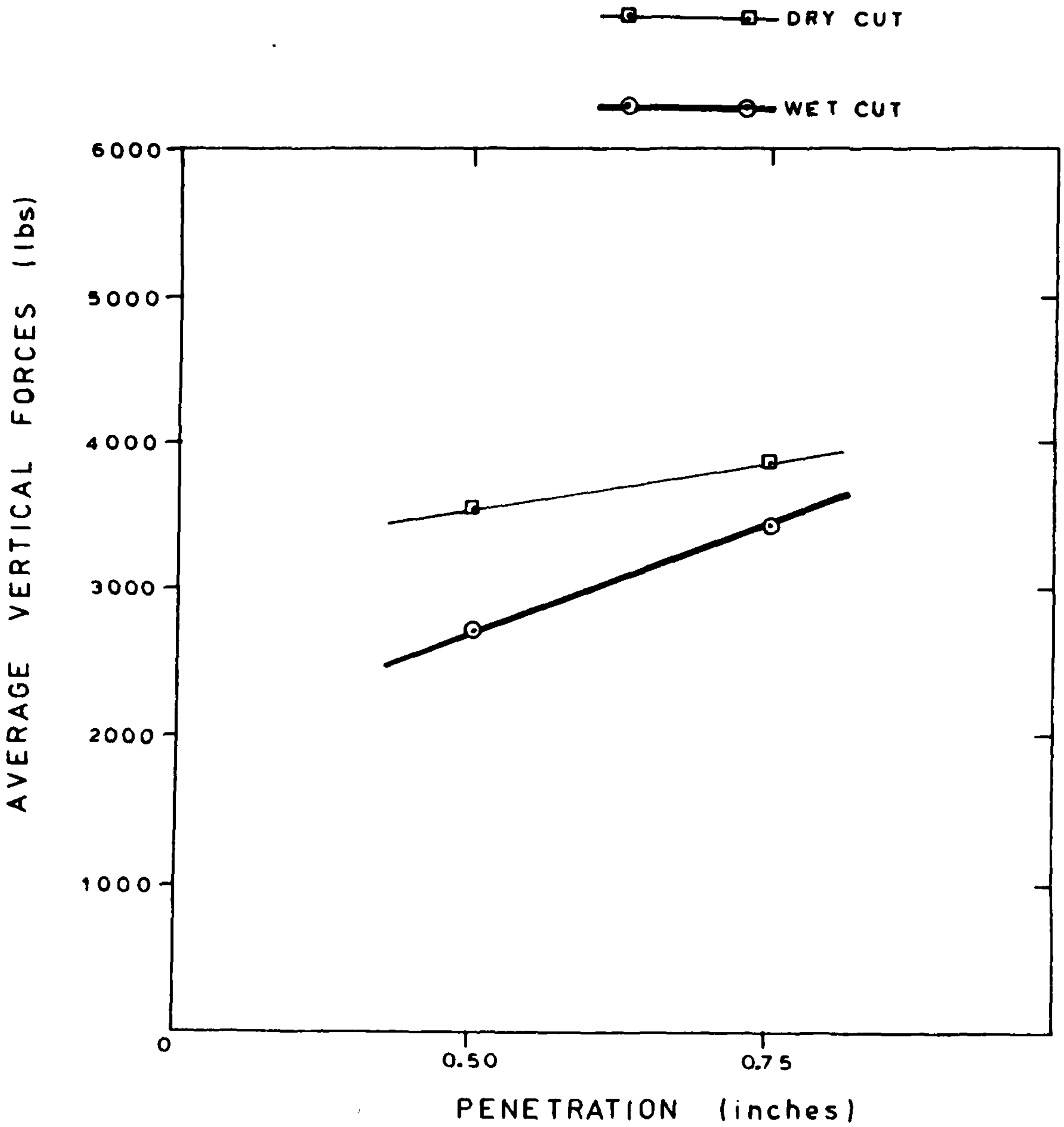


Figure 14. Average Vertical Forces vs. Penetration Depth For Zero Relief Cut.

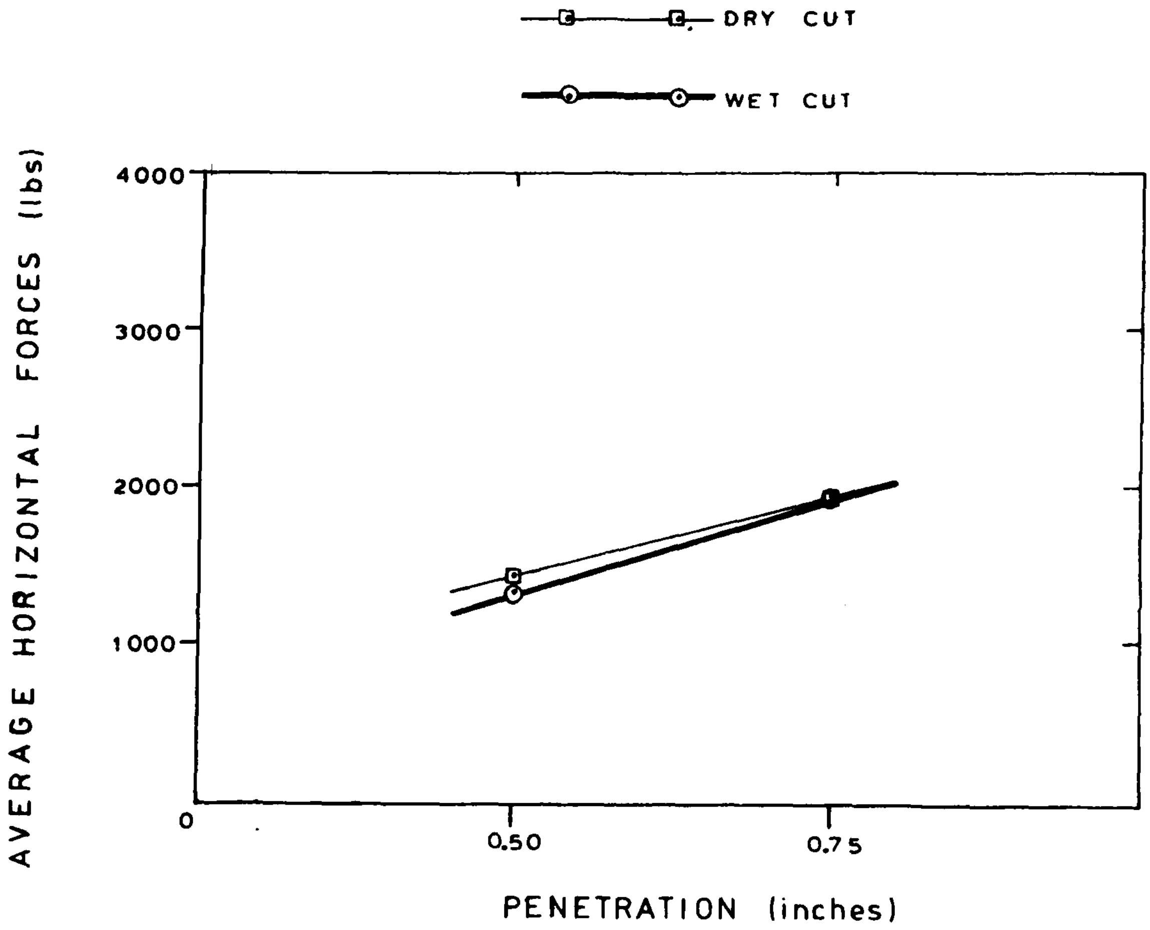


Figure 15. Average Horizontal Forces vs. Penetration Depth For Zero Relief Cut.

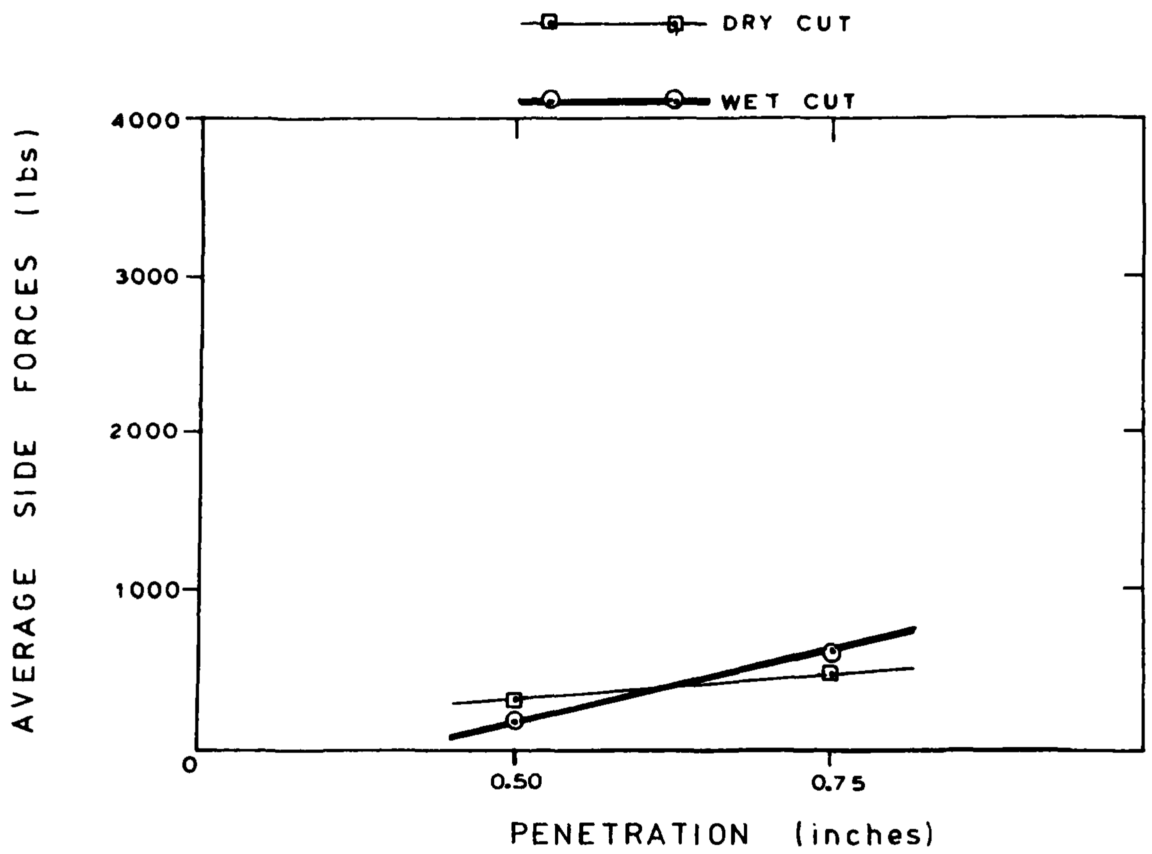


Figure 16. Average Side Forces vs. Penetration Depth For Zero Relief Cut.

SECTION IV

ENHANCEMENT OF CUTTING CAPABILITY AND PROTOTYPE CONCEPTS

1. INTRODUCTION

During the course of this program, a variety of potential approaches to enhance the cutting performance of the two technologies were proposed. In the case of the abrasive waterjet, enhancements in performance center on improvements in nozzle design and innovative methods of incorporating multiple nozzles into a concrete-cutting system. For the waterjet-assisted mechanical cutting technology, enhancements require a design optimization of a cutting system utilizing cutting picks and waterjets mounted on a cutting wheel. This section briefly discusses some possible enhancements and prototype concepts and estimates the power requirement for a system to meet the Air Force cutting goals.

2. ABRASIVE WATERJET

a. Nozzle Design

In the early part of this program, the nozzle design was identified as a crucial factor in improving the abrasive waterjet's cutting performance. Several variations of Fluidyne's nozzles were tested, indicating that factors such as the number and orientation of the jets in the nozzle and the size and geometry of the mixing chamber play an important role in cutting performance. Although further design optimization of the nozzle is attainable it is doubtful if a significant (an order of magnitude or greater) enhancement of cutting rate is achievable for a single nozzle. (Preliminary experiments, using a nozzle with six converging jets at 15,000 psi and an abrasive flow rate of 5 pounds per minute, have produced a cutting rate of approximately 0.5 ft^2/minute or approximately twice the cutting rate of the nozzle used extensively in this program.)

b. Multiple-Nozzle Systems

Even if a new nozzle design enhances the cutting capability of the technology, it is reasonable to expect that a multiple-nozzle design would be required to achieve the Air Force goal for cutting concrete. The number of nozzles, of current design, needed in a multiple-nozzle system to meet this goal can be estimated as discussed in Section III. From Figure 10, the exposure time required for a 12-inch deep cut is 10 seconds. Using the expression for exposure time and solving for the number of nozzles gives

$$n = \frac{vT}{d} = \frac{(30\ \text{ft/min})(10\ \text{sec})}{(0.25\ \text{in.})}$$

$$= 240\ \text{nozzles}$$

With 60 pump horsepower required for each nozzle, the total power requirement to achieve the Air Force cutting goal is 14,400 horsepower. This is not an accurate scaling because it implicitly includes a number of questionable assumptions. However, the point is that a large number of nozzles would be required and the power requirement is also very large.

The estimate which was made above assumes (1) that the multiple-nozzle system has all of the nozzles directed perpendicular to the concrete surface, (2) that there is no interaction between the jets in the cutting process, and (3) that all of the concrete removed was cut by the abrasive action. It may therefore be possible to reduce the number of nozzles and power requirement estimated above, by the following methods. If the multiple-nozzle system acts on the concrete from within the slot with the jets directed along the traverse direction, this will increase the exposure time of the concrete to the jet, potentially increasing the cutting rate. Another approach is to attempt to exploit the softer cement matrix and "wash out" small aggregate. These approaches are illustrated in Figures 17 and 18 and are discussed in Appendix B.

3. WATERJET-ASSISTED MECHANICAL CUTTING

The linear cutting tests provided data which can be used in designing a cutting system using this technology. In addition, the data and cutting mechanisms for concrete are very similar to those for certain rocks. The existing data base pertaining to rock-cutting applications of the technology can now be exploited. For example, data regarding the best orientation of the waterjet with respect to the cutting pick can be used to enhance the cutting rate. Appendix C contains a section which briefly reviews much of what has been learned in rock-cutting applications. Although much of these data may be relevant there is a difference in application; most of the rock-cutting applications are for mining where bulk removal of material is desired; while the application for concrete cutting is to make a narrow well-defined slot. Thus the existing data will serve primarily as a starting place in a system design optimization.

In Appendix C, three potential prototype concepts are proposed. The one which appears to be most straightforward in design is a circular cutting wheel with cutting picks and waterjets mounted on the perimeter. A schematic (Figure 19) of the system shows a side view of the wheel and top view of the whole system. The power requirement for such a system is estimated at 250 horsepower, with the production cost being approximately $90,000. A more detailed discussion of this concept and alternatives is in the Appendix.

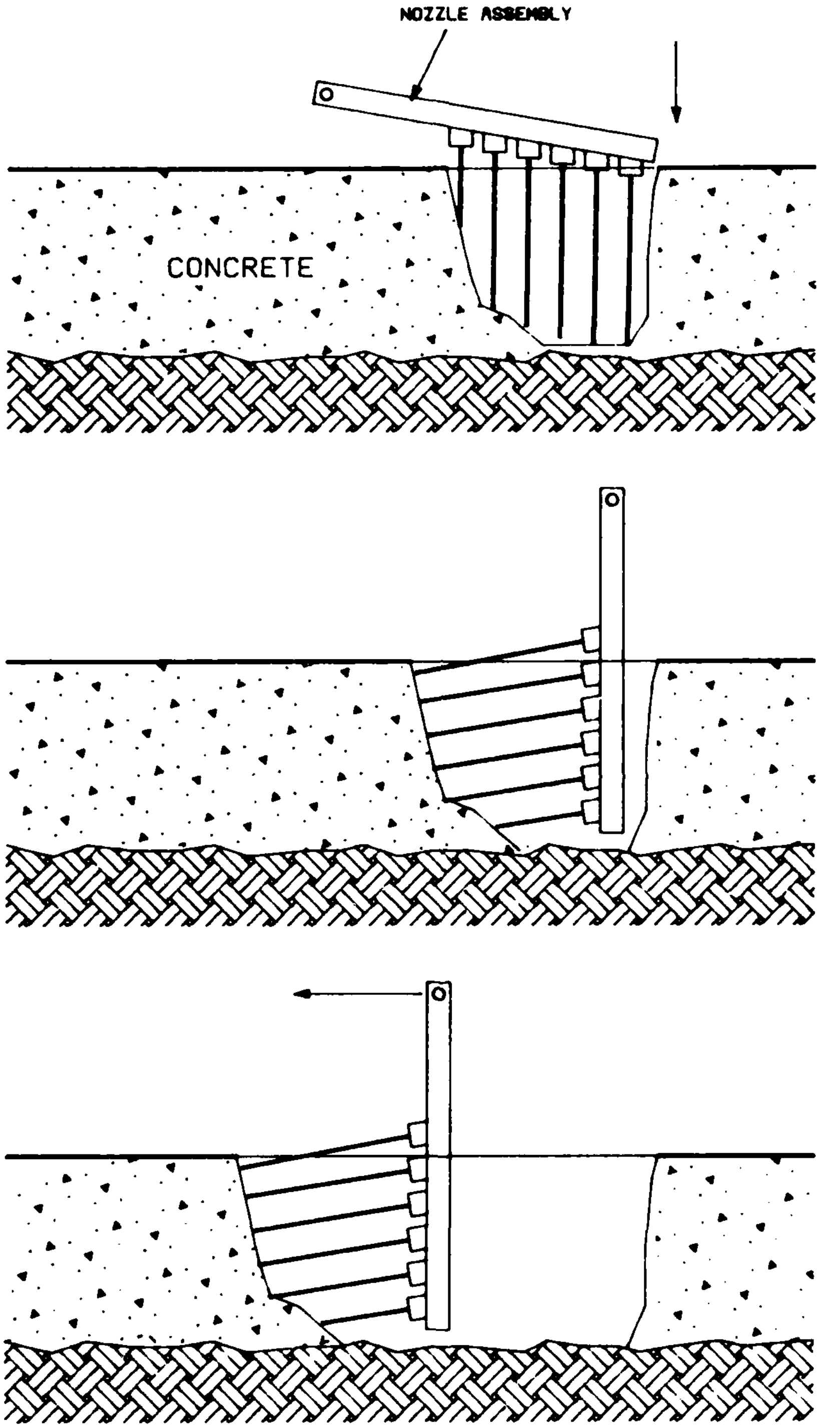


Figure 17. Vertically Advanced Abrasive Waterjet Nozzle System.

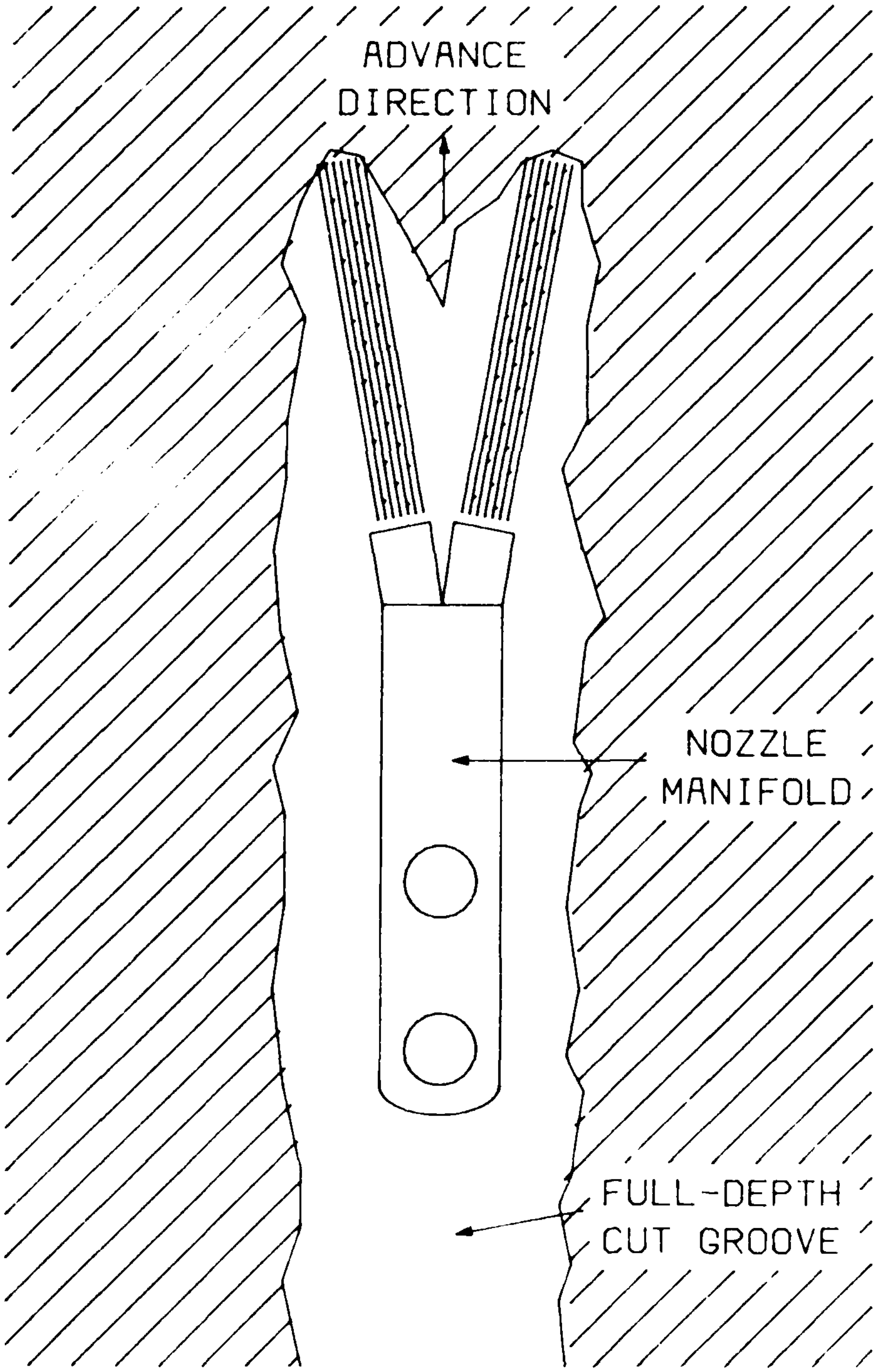
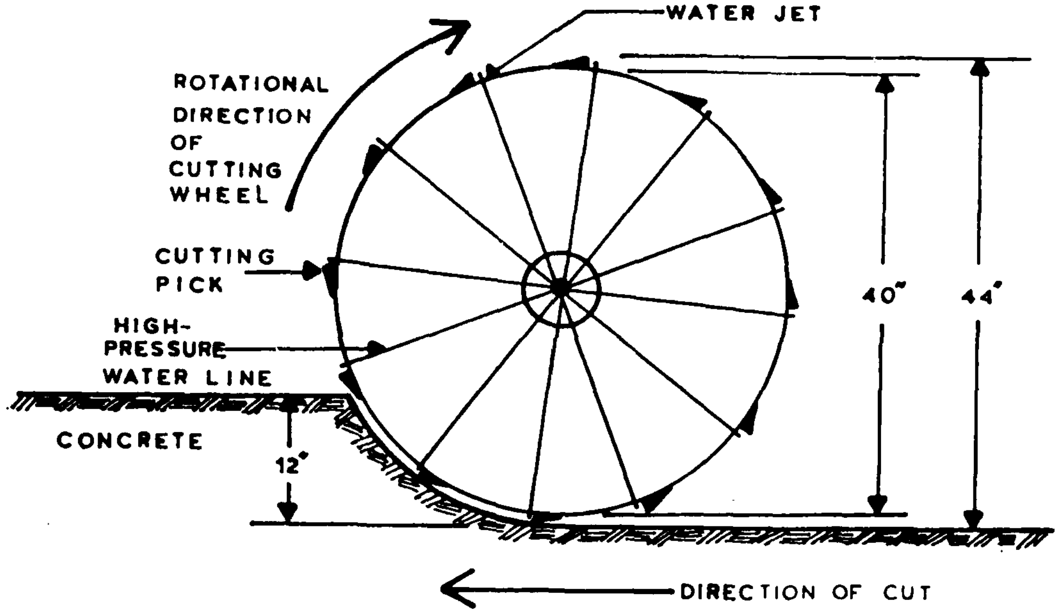


Figure 18. Top View of Nozzle Assembly in Action.

SIDE VIEW OF THE CUTTING WHEEL



PLAN VIEW OF CUTTING WHEEL MACHINE

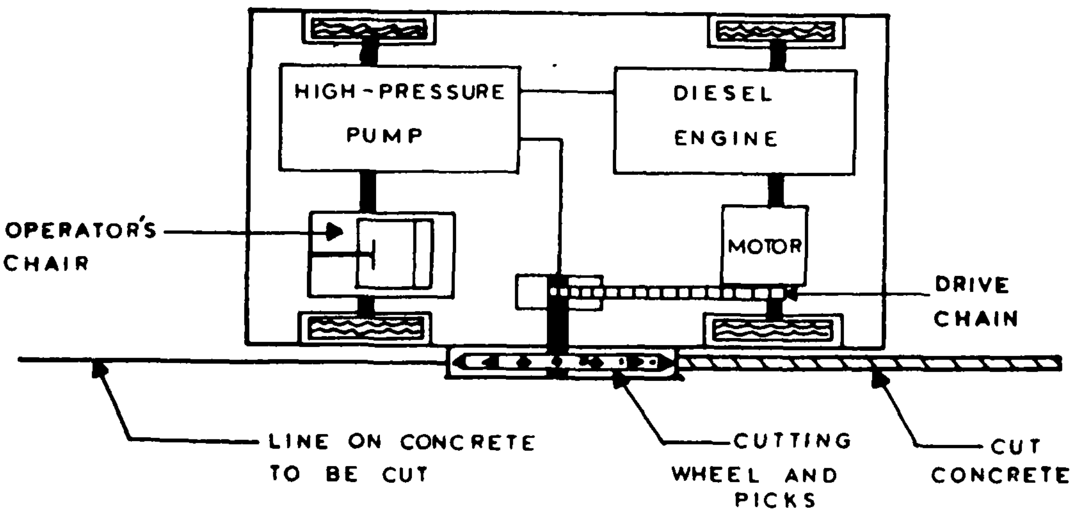


Figure 19. Cutting Wheel Prototype Concept.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this subtask was to assess the feasibility of two hybrid high-pressure waterjet concrete cutting technologies. This section uses the test program to draw conclusions about the current and future feasibility of the technologies for the Air Force concrete-cutting goals and makes recommendations regarding further research and development efforts.

1. ABRASIVE WATERJET

At the current time, the abrasive waterjet technology is not feasible for meeting the Air Force goal of a 30 linear feet per minute cutting rate in 12-inch thick nonreinforced concrete (30 ft^2/minute). The technology is still very young and, during this program, showed steady continuous progress in performance, which is expected to continue. However, the current cutting rate is approximately 0.25 ft^2/minute at 60 horsepower and it is very doubtful if the needed enhancement in capability to reach 30 ft^2/minute can be achieved in a timeframe of 1 to 2 years without a major technological breakthrough. Based on the current status and advancement of the technology, it probably also will not be able to match the cutting performance of diamond saws (4 ft^2/minute at 50 horsepower) during this timeframe.

Despite the current limitations of the abrasive waterjet technology, it does not have certain unique characteristics. It is capable of scroll cutting which would allow it to cut corners without overcutting. The abrasive waterjet is also capable of making very deep cuts. This has been demonstrated in laboratory tests with cuts as deep as 22 inches in concrete containing granite aggregate. To make such deep cuts with a single large diamond saw in a single pass would dramatically slow the cutting rate (Reference 2) of the diamond saw. A final point regarding the abrasive waterjet is that the major current limitation, which makes it infeasible, is its scaling in cutting rate with respect to power requirements; whereas, further scaling in cutting rate for the diamond saw is limited primarily in regard to the material strength of the blade.

2. WATERJET-ASSISTED MECHANICAL CUTTING

The results of the linear cutting tests indicate that the waterjet-assisted mechanical cutting technology could potentially achieve cutting rates of 30 ft^2/minute. The linear cutting tests themselves resulted in cutting rates between 4 and 10 ft^2/minute for a single pick and required approximately 21 horsepower (4 horsepower for the mechanical cutting and 17 horsepower for the waterjet). A cutting system utilizing carbide picks and waterjets on a rotating cutting wheel to achieve a 30 ft^2/minute cutting has been estimated to require a 250-horsepower engine.

Although the prospects for a system to achieve high cutting rates look promising, certain areas of technical risk remain with the cutting system. First, the data developed from the linear cutting tests are most applicable to systems removing bulk quantities of material from a surface rather than cutting a narrow slot. This shortcoming is also true of information available on mining equipment employing this technology. The impact of this deficiency makes it difficult to estimate the equipment design, power requirement, and accuracy in cut alignment. A second area of risk is associated with the quality of cut. Based on examination of the concrete specimen in the linear cutting tests, the texture of the cut face will be rough with ridges perhaps of ± 1/2 inch (Figure 5). The composition of the concrete and, in particular, the type of aggregate will affect the quality of cut; however, it is not known to what degree. The wear on the carbide picks presents another area of risk. Mining applications indicate one pick can remove approximately 4 m^3 of rock. This is equivalent to a slot 4 inches wide, 12 inches deep, and 400 feet long. Thus, a cutting wheel with 12 picks should cut approximately 4,800 linear feet before all the picks need to be replaced. As noted above, since this estimate is for mining application of bulk removal, it is not clear that it is accurate for a long narrow slot.

3. GENERAL CONCLUSIONS

Some general conclusions about concrete cutting systems can be drawn from the work of this subtask. The most energy efficient methods of cutting concrete, which can result in high cutting rates, appear to involve coupling of cutting energy through a mechanical tool. Such systems are often heavy to reduce recoil and transmit more impact to the concrete. Others are subjected to limitations by material properties such as diamond saws and carbide saws. These mechanical cutting systems also are all constrained to making straight-line cuts. To avoid these limitations, it appears necessary to sacrifice the energy efficiency of the mechanical tool. The abrasive waterjet does not have the limitation imposed by the mechanical cutting systems; however, the cutting rate is very slow compared to the mechanical systems at a comparable power level. To achieve comparable cutting rates for the abrasive waterjet will require an investment in research.

The research in this program showed that there are potential methods of augmenting the mechanical action of a cutting tool. Basically the augmentation methods exploited the material properties of the concrete. Concrete is a relatively brittle material and is much weaker in tension than in compression. The waterjet-assisted mechanical cutting technology takes advantage of these properties in a localized area by the combined action of the pick and waterjet to reduce the cutting forces on the pick.

The results of the program are summarized in Table 3, which shows the cutting rates and power requirements for the abrasive waterjet, diamond saw, and waterjet-assisted mechanical cutting tests. All of the tests were

TABLE 3. SUMMARY OF CURRENT CUTTING PERFORMANCE.

TECHNOLOGY	DEPTH OF CUT (inch)	TRAVERSE RATE (ft/min)	CUTTING RATE (ft^2/min)	POWER REQUIREMENT (hp)
ABRASIVE WATERJET	1.5	2	0.25	60
DIAMOND SAW	7.0	7	4.0	50
WATERJET-ASSISTED MECHANICAL CUTTING	0.75	160	10.0	21 (4 mechanical 17 pump)

conducted in the same type of concrete. The diamond saw has been included as a baseline for comparison.

4. RECOMMENDATIONS

The following recommendations are made regarding further research and development of the two hybrid high-pressure waterjet technologies.

a. Monitor research in abrasive water technologies, particularly in areas which could result in dramatic increases in cutting rates. This would include:

(1) Nozzle design, particularly for applications at higher power levels (greater than 60 horsepower).

(2) Research indicating a scaling in cutting rate with increased horsepower of better performance than that estimated in this report.

(3) Research in innovative system designs which result in synergistic effects.

b. Conduct testing of a model waterjet-assisted mechanical cutting wheel to provide a proof of principle and detailed design information. This approach can address the differences in the mechanics of cutting a slot versus bulk removal of material, as in mining applications. The model system should be capable of cutting rates approximately half those of a full-size prototype system. After verification of such cutting rates, a full-scale prototype system to achieve a cutting rate of 30 ft^2/minute should be designed, fabricated, and tested.

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APPENDIX A

TEST PLAN

APPENDIX A

TEST PLAN

This test plan was submitted separately to the Air Force Engineering and Services Center on June 14, 1982. It has been included in this technical report for completeness. Discrepancies between the test plan and the actual test are discussed in Section III and Appendices B and C.

1. INTRODUCTION

This test plan consists of three parts. The first part is an overview that addresses the objectives and goals of the test program and the general rationale and concepts of the test approaches to be conducted on two waterjet technologies. The remaining parts are two annexes. Annex 1 is the test plan that will be conducted by the Fluidyne Corporation in Auburn, Washington on the abrasive waterjet technology and Annex 2 is the test plan for the waterjet-assisted mechanical cutting technology to be conducted by Engineering and Science Technology, Inc., at Golden, Colorado. These two annexes provide specific objectives of the tests in addition to detailed discussions of the test procedures and equipment.

2. BACKGROUND

In conducting bomb damage repair (BDR) at airfields, numerous activities and procedures must be carried out. To expedite the speed of repair, it is desirable to investigate those activities which are slow and present a bottleneck to the whole process or permit a new repair methodology. Field tests indicate that cutting the upheaved concrete around the crater is such a rate-determining activity. An additional complication which places further constraints on the cutting is a requirement for precise controlled cutting of the concrete to dimensions and a geometry compatible with precast concrete slabs used in some BDR schemes. These considerations have provided an incentive to develop a rapid concrete-cutting system which will meet precision of cut requirements. The goal of a cutting system which can cut 30 linear feet per minute in 12-inch thick, 5,000 psi concrete with an accuracy of $\pm 1/4$ inch in 10 feet has been established by the Air Force.

In Subtask 1.06, recommendations were made for a variety of potential concrete-cutting technologies. That effort identified two promising waterjet technologies which are the subject of this test plan.

3. DESCRIPTION OF THE TECHNOLOGIES

The two technologies to be tested are the abrasive waterjet and waterjet-assisted mechanical cutting. These two technologies are at different technical stages of development which is reflected by the somewhat different emphasis of the two specific test plans in the annexes. Before discussing the test program itself, a brief description of the two technologies is valuable.

a. Abrasive Waterjet

The abrasive waterjet is a waterjet which has entrained in it abrasive particles. A straight waterjet has difficulties in cutting concrete primarily because hard aggregate can be present. The waterjet will not cut this aggregate unless the hydraulic pressure exceeds a threshold value where the rock begins to fail. This threshold pressure can be quite high for hard aggregate such as granite. The addition of finely divided hard abrasive material into the waterjet basically eliminates this problem and enhances the performance of the waterjet to cut concrete, increases speed and depth of cut, and also allows larger standoff distances. One of the major technical difficulties associated with this technology has been the introduction of the abrasive material into the waterjet without eroding or damaging the system, in particular, the nozzle, or ruining the coherence of the jet in the process of adding the abrasive. A scheme has been developed by Fluidyne which appears to avoid these pitfalls and is an aspect of the test program addressed in the appendix. In general, the technology is high risk and is at an early research and development stage. However, there have been some earlier preliminary concrete-cutting experiments which have been described in the final report for Subtask 1.06.

b. Waterjet-Assisted Mechanical Cutting

This technology makes use of a synergistic combination of two cutting mechanisms; a weakening of the concrete matrix with the waterjet and the subsequent action of the mechanical pick to remove and break the harder aggregate. Although this technology has not been applied to cutting concrete, it has been used in mining and tunneling applications. Therefore, there currently exists a body of literature and data on these applications in rock, such as sandstone and dolomite limestone. These applications have employed equipment in which mechanical cutting tools are mounted on a rotating surface that also houses the waterjet nozzles. The rotating surface is then positioned to cut into the rock. Information currently available on these applications can be exploited to augment the data developed in the test program described in Appendix B. Hence the purpose of this test program is to permit incorporation of the existing experimental data base to allow scaling estimates. This is a low-risk technology development effort.

4. THE TEST PROGRAM

a. Test Objectives

The objective of the test program is to develop the necessary data to support a feasibility assessment of the two waterjet technologies. The feasibility assessment includes the potential for the technology to meet the Air Force concrete-cutting goals, the associated costs and time requirements, and other factors which might influence BDR activities. The information necessary for this assessment will be a baseline assessment of the current capability of the technology and the development of data to

scale the equipment to meet the Air Force's goals. In developing the scaling data, the test must identify or confirm those parameters that have the largest influence on performance and the cost in scaling up the equipment.

b. Test Procedures and Approach

Because of the differences of these two technologies, such as the cutting mechanism, the current level of development and application, and the available test facilities, the test approaches and procedures also differ. However, there are certain common features. Both tests are oriented to developing data which can be referenced to cutting in a concrete of specific composition. This is discussed in more detail later. Both test programs are also conducted on a laboratory scale with multiple cuts being performed on concrete specimens. Another common aspect is that the earliest phase of testing for each technology will be debugging equipment and performing a preliminary identification of values of parameters to be used in subsequent testing. The differences in the test programs for the two technologies are discussed below.

The difference in philosophy between the two test programs described in the annexes lies in a desire to make use of existing experimental data on waterjet-assisted mechanical cutting applications, whereas such extensive data base for abrasive waterjets does not exist. The abrasive waterjet testing fundamentally proceeds by varying parameters and design aspects on what are laboratory-scale forerunners of a potential prototype system. The concept underlying the waterjet-assisted mechanical cutting test program, described in Annex 2, has a different emphasis. It is oriented toward developing the fundamental underlying data required to design a prototype system and relating this data to such systems which have already been developed for mining applications. This philosophy is in part a consequence of the testing facilities available to Engineering and Science Technology to be used at the Colorado School of Mines. The laboratory test setup makes use of a single cutting pick preceded by a waterjet which translates along the face of the concrete sample producing a kerf. A schematic sketch and detailed discussion of the test procedures are contained in Annex 2. The point to be noted here is that the data to be measured from this test can be related to the current capability of potential prototype systems similar to those for mining applications described above. The data developed in the laboratory test program can also provide the necessary scaling information for such aspects as the power requirements to drive the carbide-cutting tools and the waterjet-pressure levels, particularly when the data are correlated to those from rock cutting.

c. Concrete Specimens

The Statement of Work for Subtask 1.07 specified tests to be conducted with test samples containing mountain stone granite. Tests will be conducted for both technologies on concrete samples containing this aggregate. Detailed specifications for the samples are given in Table B-1 of Appendix B. Because of the early stage of development of the abrasive jet

technology, a large number of tests are planned to investigate numerous combinations of parameters. To allow for this comprehensive test effort, the majority of the tests will be conducted on less expensive concrete specimens containing local aggregates of approximately equal hardness. The tests also develop the data needed to correlate the effects of the different aggregates which are anticipated to be minor, as will be discussed later. In the test plan for the waterjet-assisted mechanical cutting, the large number of additional tests is not as urgently needed because these have, in a sense, already been conducted in the existing data and literature on rock-cutting applications. Thus, testing, which provides a correlation of concrete cutting to rock cutting, is needed but not nearly as comprehensive a program as for the abrasive waterjet.

d. Anticipated Results

Part of the test effort will be to identify those parameters and design characteristics which have the most significant impact on the cutting speed and alignment. The identification is of key importance in developing accurate scaling information. This section of the test plan will briefly discuss those parameters anticipated to have the most dramatic effects on system performance.

(1) Abrasive Waterjet. The power level of the abrasive waterjet is anticipated to be the major scaling factor determining the cutting performance with this technology. The power level is proportional to both jet pressure and flow. As discussed earlier, a straight waterjet will have to exceed a certain threshold pressure to be able to cut hard aggregate. Currently, it is believed that the introduction of hard abrasive material in the jet dramatically lowers that threshold pressure or may eliminate it completely. It is also anticipated that the pressures for the cutting tests will be substantially above the threshold pressure and that the cutting performance will be determined primarily by the total power (Note: Power $\propto \Delta p \times$ Flow) and will be less affected by changes in flow rate and pressure at a constant power level. The substitution of different but approximately equally hard aggregate in the concrete experiments, as proposed by Fluidyne, should not affect the results and even the substitution of a harder aggregate should not cause adverse effects.

Another parameter which is believed to exhibit large effects on the cutting performance is the nozzle configuration of the abrasive jet. The nozzle configuration will, to a large extent, determine the quantity of abrasives entrained in the jet and the resulting coherence of the jet. There is a certain trade-off involved because introducing more abrasive will enhance the cutting performance while at the same time it could reduce the coherence of the jet, causing a detrimental effect on performance. It is believed that changes in this design parameter could have the most dramatic effect on cutting performance observed in the tests. However, it should be noted that this is not a scaling parameter, as is the jet power level.

(2) Waterjet-Assisted Mechanical Cutting. The parameters which will play a major role in the waterjet-assisted mechanical cutting technology are not quite so easily isolated. This is because the technology involves a coupling of two effects: the weakening of the concrete matrix by the waterjet, and cutting the resulting weakened concrete with a cutting tool. There are anticipated optimal combinations of parameters, in particular, the waterjet pressure and flow rate with the "bite" depth of the mechanical cutting tool. The test approach described in the annex will allow for determining when the parameters are appropriately tuned to cause these effects. In addition, relationships between these effects and the concrete composition, especially aggregate size, will be carefully examined.

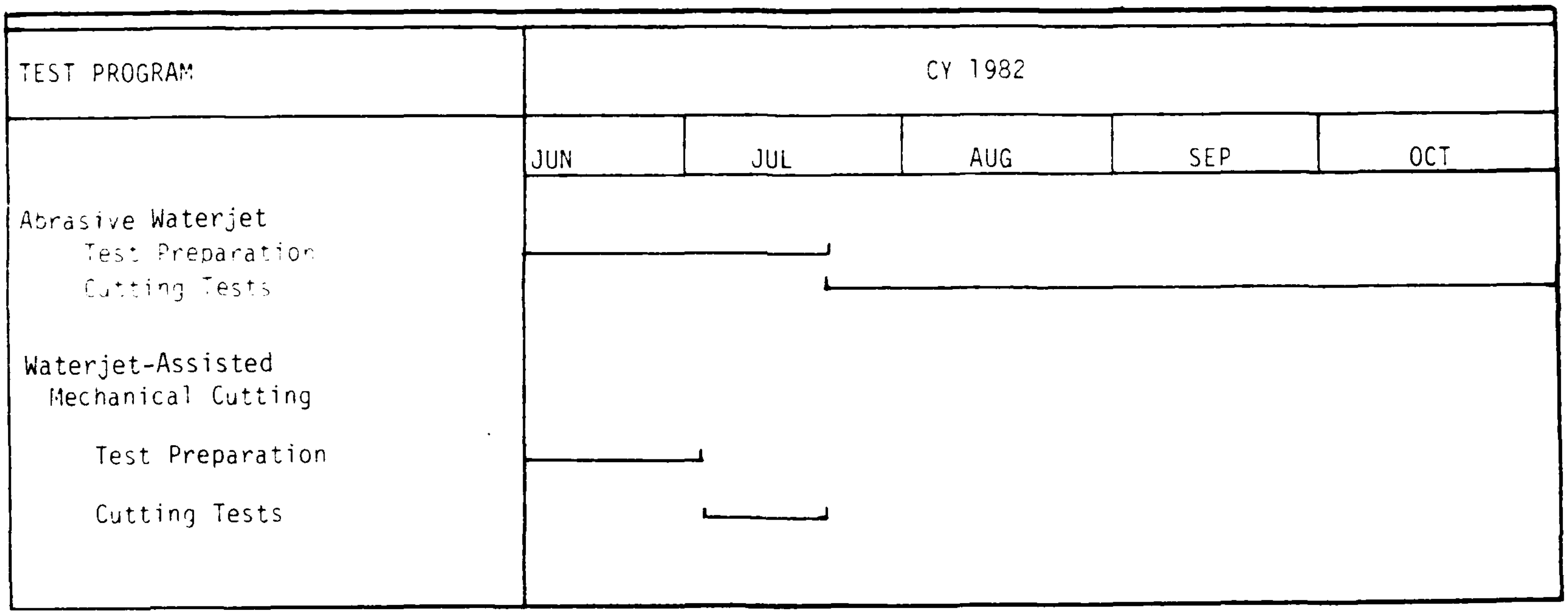
5. SUMMARY

Based on the data obtained from this waterjet technology test program, the feasibility to achieve the Air Force goal of cutting 30 feet per minute in 12-inch thick portland concrete using either the abrasive waterjet or the waterjet-assisted mechanical cutting technologies will be assessed. If feasibility is demonstrated, the technology (or technologies) will be conceptually scaled to estimate the size, power and other important engineering parameters necessary to assess the cost and risks associated with continuing to develop this concrete-cutting concept.

6. SCHEDULE

The schedule for the test plan is in Table A-1. More detailed schedules, breaking out various test phases, are contained in the two annexes to this appendix.

TABLE A-1. TEST PHASES.



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ANNEX 1

CUTTING CONCRETE WITH ABRASIVE WATERJET TEST PLAN

PREPARED BY FLUIDYNE CORPORATION, AUBURN, WASHINGTON, FOR THE BDM CORPORATION, MAY 1982.

ANNEX 1

CUTTING CONCRETE WITH ABRASIVE WATERJET TEST PLAN

1. OBJECTIVES

The specific objectives of the proposed test are as follows:

- To observe the performance of test nozzles in jet coherence, flow rate, suction generation and abrasive entrainment.

- To conduct linear cutting test on concrete specimens with selected nozzles at prescribed conditions.

- To compile data on the effect of selected system parameters on the depth, width and quality of cut made on concrete.

2. TEST DESCRIPTIONS

a. Test Criteria

(1) Jet Configurations. In this program, the test nozzles will have interchangeable inserts that allow the jet configuration, flow rate and power output to be varied. Figure A-1-1 shows Fluidyne's proprietary nozzle. The interchangeable insert is denoted as the orifice plate in the figure. Five jet configurations will be studied in which the nozzle inserts will be used to generate 6, 5, 4 and 3 parallel jets and a single jet. In the case of multiple parallel jets, the jets will be arranged in a circular pattern to provide a central area for entraining abrasives. These parallel jets can generate very strong suction well-suited for feeding abrasives into the waterjets.

(2) Water Pressure and Power Input. The selected nozzle inserts also allow the five jet configurations to be studied at a fixed power input of 60 horsepower (rated power of an electric motor) and at three different water pressure levels--10,000, 15,000 and 20,000 psi. To achieve this objective, the selected nozzle inserts will have orifices that are calculated to accept the available power input and to deliver the full flow provided by the pump. A total of 15 nozzle inserts will be needed for this portion of the test. Other selected nozzle inserts will also be employed to generate abrasive waterjet at less than the available 60 horsepower; two power levels of 20 and 40 horsepower will probably be selected for testing. Since the reduced power is to be achieved by bleeding a portion of the high-pressure water, the exact power output of the nozzle can only be estimated in such partial power cases. These three power levels will allow the cutting data to be extrapolated to much higher power inputs.

(3) Test Equipment. To conduct these tests a high-pressure pump unit for pressurizing water to 20,000 psi will be needed. This pump will

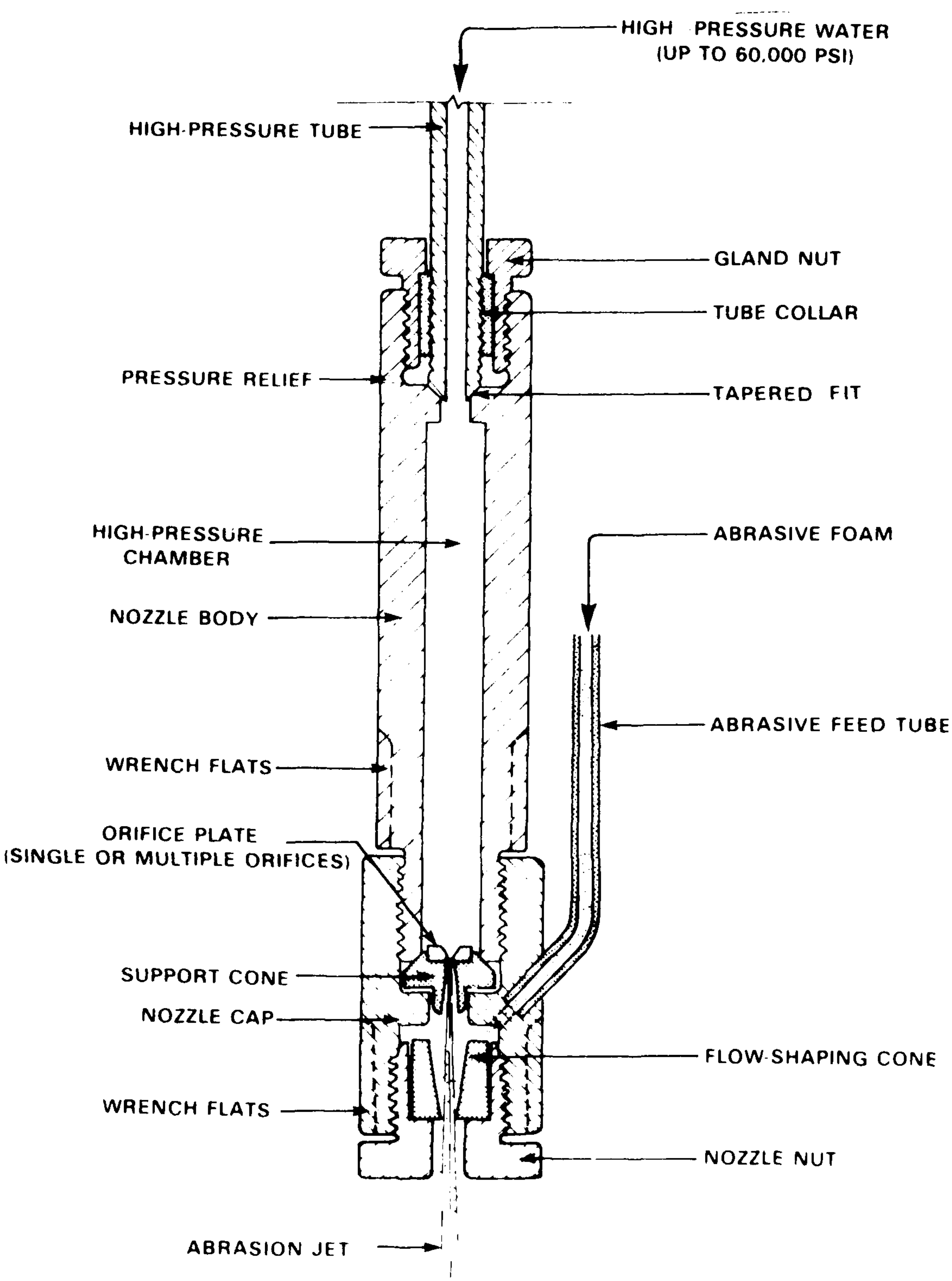


Figure A-1-1. Abrasive Waterjet Nozzle.

be driven by a 60-horsepower electric motor and will be operated at 500-550 rpm. In addition, a nozzle-traverse setup and a complete fluid monitoring and control system are also required. A system for feeding selected abrasives to the nozzle under control is also required. Figure A-1-2 is a schematic illustration of the major components in the test setup. These components are currently being assembled.

(4) Dependent Variables. The concrete-cutting capability of test nozzles will be judged by the depth, width, equality and accuracy of cuts that they produce on concrete specimens under prescribed conditions. By measuring the volume of cuts with wax, a specific concrete remote rate in cubic inches per second per given power level can be computed. This figure can be used to compare the concrete-cutting capability of Fluidyne's abrasive waterjet with other techniques.

(5) Independent Variables. The independent variables of this test program will be jet configuration, water pressure and flow rate, nozzle traverse speed, nozzle standoff distance, and abrasive loading. These independent variables will be covered in this program on a selected basis rather than a matrix of many combinations. The optimum value of each independent variable, if identified, will be selected for in-depth cutting tests. The optimization of system parameters will not be performed in this program.

(6) Concrete Specimens. The concrete specimens to be used in this program will measure 16 inches by 16 inches by 8 inches for easy handling. They will have a minimum compressive strength of 6,000 pounds per square inch after curing for 28 days. These slabs will contain locally available Steilacoom aggregates that are a mixture of six to seven different kinds of igneous rocks, known for their hardness. Some of these concrete slabs will contain No. 5 steel rebars for testing the ability of abrasive waterjet in cutting steel. A total of 20 such concrete slabs are currently planned and will be cast by the Concrete Technology Corporation, located in Tacoma, Washington. This company has R&D capabilities in concrete technology.

In addition to the concrete specimens described above, another concrete specimen will be prepared containing Georgian mountain stone granite aggregate. This sample will provide baseline data which can be used to correlate the data developed using the Steilacoom aggregate concrete specimens to equivalent tests with the granite aggregate.

(7) Abrasives. The abrasives to be used in this program will be garnet and silica sand of selected grain sizes. The exact grain sizes to be selected for testing have yet to be determined. An initial screen will be performed to check out the flow of abrasives under nozzle suction. Limited testing will also be performed with Fluidyne's proprietary abrasive foam slurries made with selected garnet abrasives.

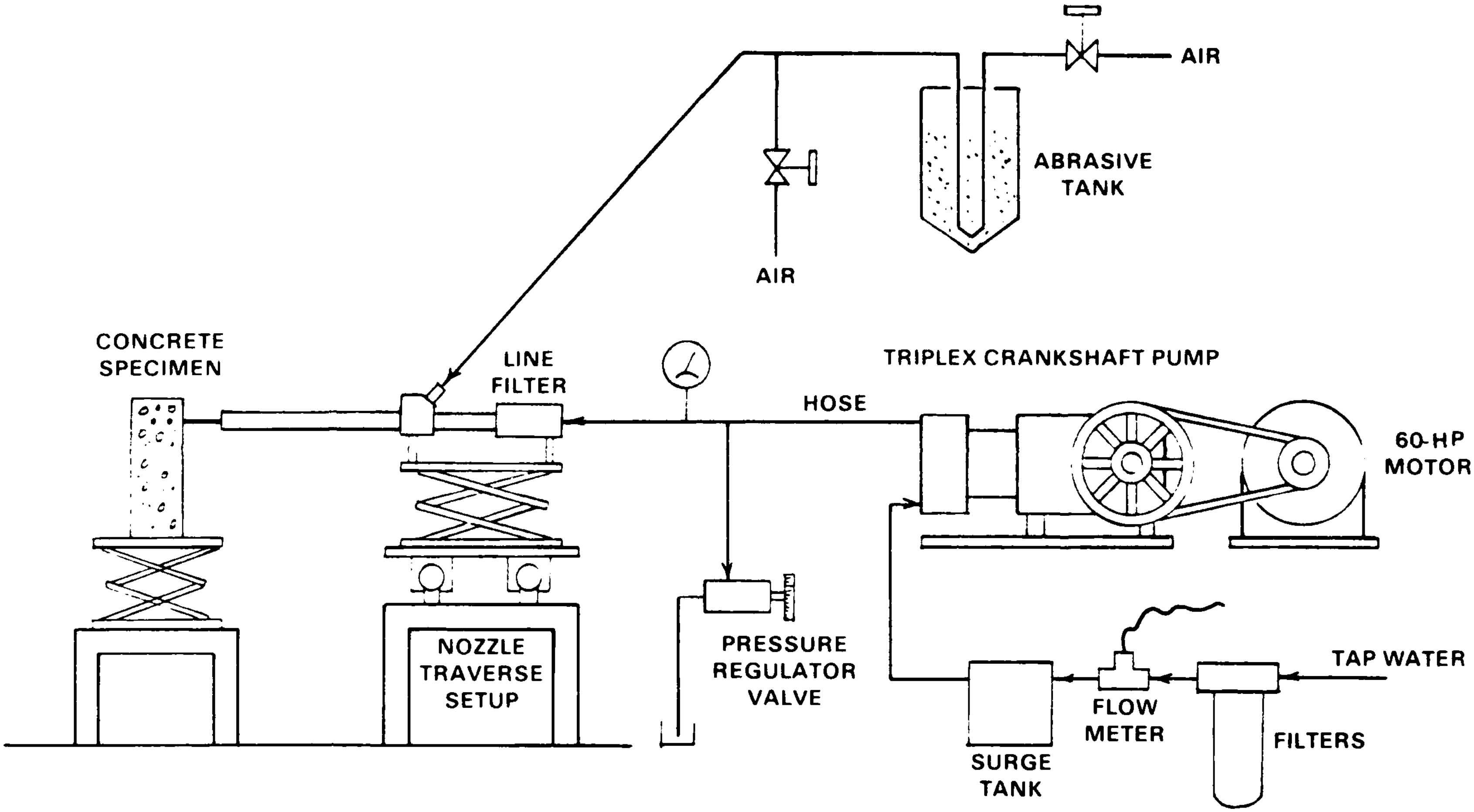


Figure A-1-2. Schematic Illustration of System Components of an Abrasive Waterjet Concrete-Cutting System.

3. TEST PROCEDURES

a. Task 1 Preparations

The first three months of this program will be geared to preparing for the cutting tests. This task includes efforts in different endeavors such as procurement of components and materials, fabrication and assembly of parts and subsystems, and initial testing and debugging of subsystems. Basically, the pump unit will be undergoing shakedown, the flow meter for measuring water consumption will be calibrated, the nozzle traverse system will be checked out and the speed control calibrated, and the abrasive feed system debugged. The test nozzles and the selected nozzle inserts will be tested under water pressure to observe the jet quality and to make necessary adjustments. One aspect that will be observed closely in this task is the level of suction or vacuum generated by the nozzles and how this suction is related to the transport of abrasives through hoses and to the abrasive entrainment inside the nozzle.

b. Task 2 Cutting Test

As indicated previously, the concrete-cutting test will be performed at three levels of static water pressure: namely, 10,000, 15,000 and 20,000 psi. The test will be initiated at 20,000 psi and the water pressure will be lowered to 15,000 and 10,000 psi later; changing the system pressure requires the installation of appropriate high-pressure cylinders and plungers at the pump. The inability to readily change the system pressure is one of the weak points of crankshaft plunger pumps. Table A-1-1 summarizes testing to be conducted at 20,000 psi.

At the selected water pressure and full 60-horsepower input, a test nozzle having the desired insert will be mounted on the traverse stand for checking the effect of three system parameters, namely, nozzle standoff distance, traverse speed, and abrasive loading. The nozzle standoff distance is readily adjustable from the nozzle traverse stand; three values of 0.5, 1.0 and 1.5 inches are currently planned. The nozzle traverse speed will be varied between 2, 3 and 6 inches per second (equivalent to 10, 15 and 30 feet per minute). The levels of abrasive loading to be selected for testing are still undetermined but will be decided upon completion of Task 1. The subject of abrasive loading will require some investigative effort as the grain size of abrasive is believed to be related to the granular structure of rock in abrasive waterjet cutting.

Once the test parameters are decided, a linear, one-pass cut will be made on the concrete specimen. Three parallel cuts with 1-inch spacing will be made for each set of system parameters. Afterwards, the nozzle will be traversed again to make two-pass and four-pass cuts. Additional multiple-pass cuts may also be performed, pending the results of the four-pass traverse. The multipass cutting data will provide information on the design and application of compound abrasive waterjet nozzles.

TABLE A-1-1. TESTS AT 20,000 psi.

VARIABLE	TEST 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NUMBER OF JETS	1	1	1	3	3	3	4	4	4	5	5	5	6	6	6
POWER (HP)	60	40	20	60	40	20	60	40	20	60	40	20	60	40	20
TRAVERSE SPEED[2] (FT/MIN)	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]	[10 15 30]
STANDOFF DISTANCE[2]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]	[0.5 1.0 1.5]
NUMBER OF PASSES[2]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]	[1 2 4]

[1] A SIMILAR BUT POSSIBLY MORE SELECTIVE SET OF TEST WILL BE CONDUCTED AT 15,000 AND 10,000 psi.

[2] THE ENTIRE RANGE OF THESE VARIABLES WILL NOT BE INVESTIGATED IN EVERY TEST; ONLY SELECTED ONES.

The tests previously described will be repeated with other selected nozzles and inserts until the water pressure must be changed. After installing the different high-pressure cylinders and plungers on the pump, the tests will be resumed. It is not decided at present if the entire test procedure will be repeated at 15,000 and 10,000 psi levels; a decision will be made after comparing the cutting results obtained at different water pressures. If the cutting at 15,000 psi water pressure is sufficiently good, extensive testing will be pursued in this program. Similar practice will be applied to cutting at 10,000 psi water pressure.

The above tests will be supplemented with the tests conducted on the control concrete test specimen containing granite aggregate. These tests will be conducted at 20,000, 15,000, and 10,000 psi at each of the following power levels: 60, 40 and 20 horsepower. The remaining parameters, number of jets, standoff distance, and traverse speed, will be held constant at optimum values determined by the major test effort.

After completing the test with each concrete slab, the slab will be removed from the cutting booth, which is an area isolated with concrete borders and shower curtains, and carefully examined. The width and depth of cuts will be measured and wax will be poured into the cut for measuring the volume of cuts. By so doing, accurate measurement of the concrete removed by the abrasive waterjet can be made. By relating the volume of concrete removed to the energy contained in the waterjet and the time duration of the nozzle traverse, a specific concrete removal rate of the abrasive waterjet can then be computed.

c. Test Equipment and Facilities

(1) Pump Unit. The pump to be used in this test program will be a triplex crankshaft plunger pump manufactured by Butterworth, Inc., of Houston, Texas, capable of delivering 4.7 gpm water at a maximum pressure of 20,000 psi. The power requirement is 60 horsepower at 500-550 rpm. This pump will be driven by a 60-horsepower three-phase electric motor operating at 1750 rpm through speed-reducing sheaves and belts. A magnetic starter will be installed with the pump unit. Such crankshaft pumps come in a wide variety of flow capacity and power rating; most of them have a pressure capability of less than 20,000 psi maximum. Reliability, availability, and simplicity in operation are strong points of this type of pump; lack of adjustment in pressure and flow rate is its weak point.

(2) Water Filtration. Tap water will be used in this test program. The water will be filtered to a minimum particle size of 5 microns to insure the removal of particulates which will prolong the life of pump parts and nozzle orifices. Two sets of filters will be employed; paper cartridge filters will be used at the low-pressure end and metal cup filters will be employed at the high-pressure end. This arrangement will improve the life of the pump seals and check valves as well as the sapphire orifices; several hundred hours of operating life can be expected with the sapphire orifices.

(3) Nozzle Traverse Setup. The nozzle traverse system (Figure A-1-2) is basically a structure that provides the desired movement to the abrasive waterjet nozzle, which is to be mounted at the tip of a long high-pressure tube. The pressurized water will be transported from the pump to the traverse stand through a high-pressure hose. The nozzle traverse system provides movement in all three directions--horizontal movement in the X-Y plane and vertical movement in the Z direction. The X-direction movement will be provided by means of a gearmotor with speed control; interchangeable sprocket further adds flexibility in the speed control. The vertical and forward/backward movement of the nozzle will be manually operated. The test nozzle will be mounted in a horizontal position while the concrete specimen will be placed on a vertical position. Thus, the traverse of the nozzle will make a horizontal cut across the concrete specimen's vertical face. By adjusting the vertical position of the nozzle and the height of the concrete slab, many parallel cuts can be made on the surface of each concrete slab. Scissored jacks will be used for adjusting the height of nozzle and concrete specimen. Sliding bearings and polished steel rails will be employed to provide smooth sliding of the nozzle stand.

(4) Control Console. A central control console will be provided and will be placed next to the nozzle traverse stand. This control console will have a start-stop switch for the pump unit, a water pressure indicator and regulator, a water flow rate indicator, a nozzle traverse switch and speed control, and a visual port for observing abrasive flow. An abrasive sampling port is also contemplated but remains to be designed.

(5) Test Nozzles. The nozzles that will be used in this test program will be Fluidyne's proprietary abrasive waterjet nozzle (Figure A-1-1) with interchangeable orifice cones and flow-shaping cones. The orifice cones are made of stainless steel with selected sapphire orifice jewels mounted on top. These orifice cones come in five configurations, having 6, 5, 4, 3, and 1 orifices. Since the size of the sapphire orifice is keenly related to the flow rate, each configuration will have different orifices for each of the three water pressure levels. A minimum of 15 orifice cones will be made ready for this program. The flow-shaping cones are used for generating suction downstream of the orifices; they are made of hard ceramics and are sized according to the jet configurations. It is not clear how many of these ceramic cones are required for this test program as Fluidyne's nozzles allow some adjustment to the position of this flow-shaping cone; they will be made during the course of this program.

(6) Abrasive Feed System. Feeding abrasive powder into the nozzle under fine control will require special equipment; commercial sandblasting equipment is too crude for this program. Fluidyne has a proprietary feed system design involving the application of a fluidized-bed principle to transport abrasive particles and the use of air by-pass adjustment to eliminate the need for abrasive valves. A prototype of this feed system will be used in this program to handle abrasives. The measurement of abrasive flow will be made by batch sampling and weighing the particles; onstream measurement is deemed too expensive for this program.

4. SCHEDULE

The schedule of this test program is shown below.

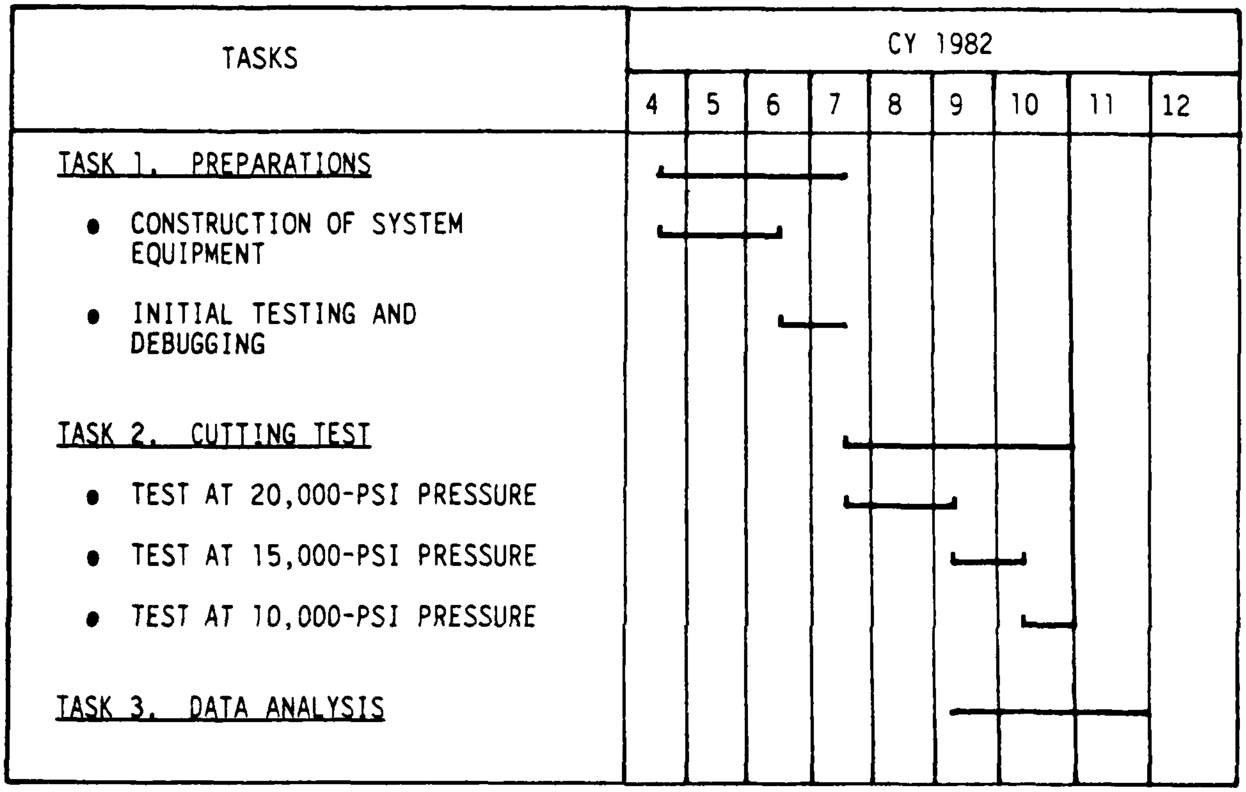


Figure A-1-3. Schedule for Test Plan for Rapid Concrete Cutting.

ANNEX 2

WATERJET-ASSISTED MECHANICAL CONCRETE-CUTTING TEST PLAN

PREPARED BY ENGINEERING AND SCIENCE TECHNOLOGY, INC., GOLDEN, COLORADO FOR THE BDM CORPORATION, MAY 1982.

ANNEX 2

WATERJET-ASSISTED MECHANICAL CONCRETE-CUTTING TEST PLAN

1. OBJECTIVES

The objectives of the laboratory experiments are: (1) to obtain basic waterjet kerfing data, (2) to obtain mechanical pick concrete-cutting base data, and (3) to obtain waterjet-assisted mechanical concrete-cutting data. These data will also provide a means of correlating rock cutting and concrete cutting such that rock-cutting methodology and data may be used for predicting concrete-cutting characteristics.

2. TEST DESCRIPTION

a. Types of Tests

The approach to be used in this test program develops data in three phases of laboratory experiments. The first phase will investigate parameters associated with waterjet kerfing of concrete. In the second phase, mechanical pick cutting tests will be conducted on the concrete specimens to develop reference data. The data developed in the first two phases will be used to establish parameters for the waterjet-assisted mechanical cutting tests of the third phase. Each of these three phases is discussed in more detail below.

(1) Waterjet Kerfing Tests. In these tests, the effectiveness of waterjet cutting of concrete will be investigated for the following parameters:

(a) Standoff distance: 1.0 to 3.0 inches.

(b) Nozzle size: 0.012 inch and 0.025 inch.

(c) Water pressure: 5,000 and 10,000 psi.

(d) Jet traverse velocity: 20 in./sec with 30 in./sec optional.

The depth of kerf will be recorded and analyzed. This information will then be used in selecting the waterjet parameters to be used in the waterjet-assisted mechanical cutting tests.

(2) Mechanical Pick Cutting Tests. These tests will establish base or reference data for evaluating the effectiveness of waterjet-assisted mechanical concrete cutting by comparing the reduction of cutting forces.

The test parameters are:

(a) Depth of cut: 1/2 inch - 3/4 inch.

(b) Spacing between cuts: 1/2 inch - 1 inch.

(c) Traverse velocity: 20 in./sec; 30 in./sec optional.

The cutting forces, vertical, horizontal, and side forces will be recorded and analyzed. These data will also be used to establish parameters for the mechanical pick in the third-phase testing.

(3) Waterjet-Assisted Mechanical Cutting Tests. These tests will investigate waterjet-assisted mechanical concrete cutting. The resulting data will provide a baseline assessment of the current capability of the technology. A comparison of this data to data obtained from the second phase tests will measure the enhancement in cutting when the mechanical pick is coupled with the waterjet.

Specific values of the parameters to be used in conducting the tests will not be established until the tests in the first two phases are completed. However, tentative values of these parameters are given below:

(a) Standoff distance: 2 inch.

(b) Nozzle size: 0.025 inch.

(c) Water pressure: 10,000 psi.

(d) Jet and mechanical cutter traverse velocity: 20 or 30 inches/sec.

(e) Depth of cut: 1/2 inch - 3/4 inch.

(f) Spacing of cut: 1/2 inch - 1 inch.

During the tests, the cutting forces, vertical, horizontal, and side forces will be recorded, analyzed, and compared to results obtained from the second phase.

3. TEST PROCEDURES

Procedures for testing concrete cutting are identical to the rock cutting except with different parameter values. The testing procedures include sample preparation, equipment calibration, testing and linear cutting machine operation, waterjet operation, and data collection.

a. Sample Preparation

Two small concrete samples of 12 inches by 12 inches by 6 inches will be prepared for waterjet kerfing tests.

The composition and specification of the small samples are identical to the large sample of 24 inches by 24 inches by 30 inches. The concrete samples are mixes of Type 3A cement with granite gravel of less than 3/4-inch size and No. 400 sand with water to cement ratio of 0.47 with uniaxial compressive strength of 6,000 psi after 28 days. The detail specification and composition are listed in Table A-2-1.

One large concrete sample will be used for obtaining all test data and two samples will be used for spares in case the first sample cracks during testing.

b. Calibration

Prior to cutting tests, the linear cutting machine will be calibrated for its load-recording accuracy. A static test will be performed by applying a known loading with a hydraulic ram to the pick cutter.

The three forces, vertical, horizontal, and side, resulted from the applied load and the orientation of the applied load will be calibrated against the measured output from the strain gage bridges on the cutting head load cell. The load integrators will also be calibrated with a known applied load.

c. Testing and Linear Cutting Machine Operation

In all the tests, the bit is to be held at a set penetration depth into the concrete, and the thrust and drag forces resulting from moving the bit across the concrete are to be monitored. The individual force on an individual bit can vary greatly as a machine operates, while the penetration rate remains fairly constant because of the overall stiffness of the system.

The high bit-concrete stresses to be produced by drag-bit cutting in concrete may cause both chipping of the material and also induce microcracks. These microcracks will affect the cutting forces on the bit and are dependent on the type of bit, spacing between cuts, and penetration depth. To reduce variability in the results from the effects of these cracks, the concrete surfaces will be conditioned with a series of cuts before a test run is to be made.

d. Waterjet Operation

The waterjet nozzle assembly will be mounted on the bit mounting plate in the orientation of the waterjet relative to the cutting surface of the bit. This is to be done by using slip-type swivel joints to allow

TABLE A-2-1. SPECIFICATIONS FOR CONCRETE TEST SAMPLE.

Designation	Cured Concrete w/ Granite Aggregate
Sample	24 inch x 24 inch x 30 inch
Sample Composition:	
Type 3A Cement	1 part by weight
Concrete Sand Sidley No. 400	1.9 parts by weight
Georgian Mountain Stone Granite Aggregate	2.8 parts by weight M-6: 1/2 inch to 3/4 inch, 75 percent M-89: 1/16 inch to 1/2 inch, 25 percent
Water/Cement Ratio	0.47 by weight
Concrete Properties:	
28th Day Compressive Strength	6,000 psi minimum

Test sample to be supplied by:

Columbus Cement Products Co.
1165 Alum Creek Drive
Columbus, Ohio 43209
(615) 252-0955

exact positioning of the nozzle. The jet is positioned and tested under pressure so that the waterjet is aligned with the drag bit.

In making the waterjet-assisted cuts, the concrete is to be positioned in front of the bit and nozzle. Then the waterjet is to be turned on and the concrete pushed toward the bit.

Upon completion of the cut, the jet is turned off and the concrete pulled back. The concrete sample is then shifted laterally to the desired spacing between cuts and the procedure repeated.

e. Data Collection

The data for the vertical, drag, and side forces on the bit are to be collected and integrated electronically to provide a total force per cut for each of the three directions. The depth of cut, the cutting speed, water pressure, and spacing of cut are to be recorded on each cut.

4. EQUIPMENT

The equipment to be used in the test program consists of four major components: (1) the drag bit and its mounting block and load cells, (2) the linear concrete-cutting machine, including the main frame and sample box with a hydraulic ram for linear translation, (3) the instrumentation to monitor the forces required to cut the concrete, and (4) the high-pressure waterjet system (Figures A-2-1 and A-2-2).

a. Drag Bits

The pointed conical or plumb bob-type pick cutter is to be used for concrete cutting. A tungsten carbide insert is attached at the tip. This bit is designed for mounting at a 45-degree angle to the concrete surface and is designed to freely rotate axially in its mounting so that the tip is self-sharpening and maintains a constant cutting profile.

The pick cutter is attached to the mounting block, which is rigidly fastened to the underside of the load cell on the linear concrete cutter used to measure the normal and drag forces.

b. Linear Cutting Machine

This unit supports the concrete sample and the cutting tool and controls the interaction between them. The unit is designed to test full-sized rock/concrete cutters under actual loading conditions and can withstand large dynamic loads with minimal deflection or vibration. A stationary overhead frame holds the cutting tool while the concrete sample below is driven horizontally into the pick cutter.

The main frame consists of large welded and bolted steel beams. The cutting tool is suspended under the large boxed crossbeams and can be

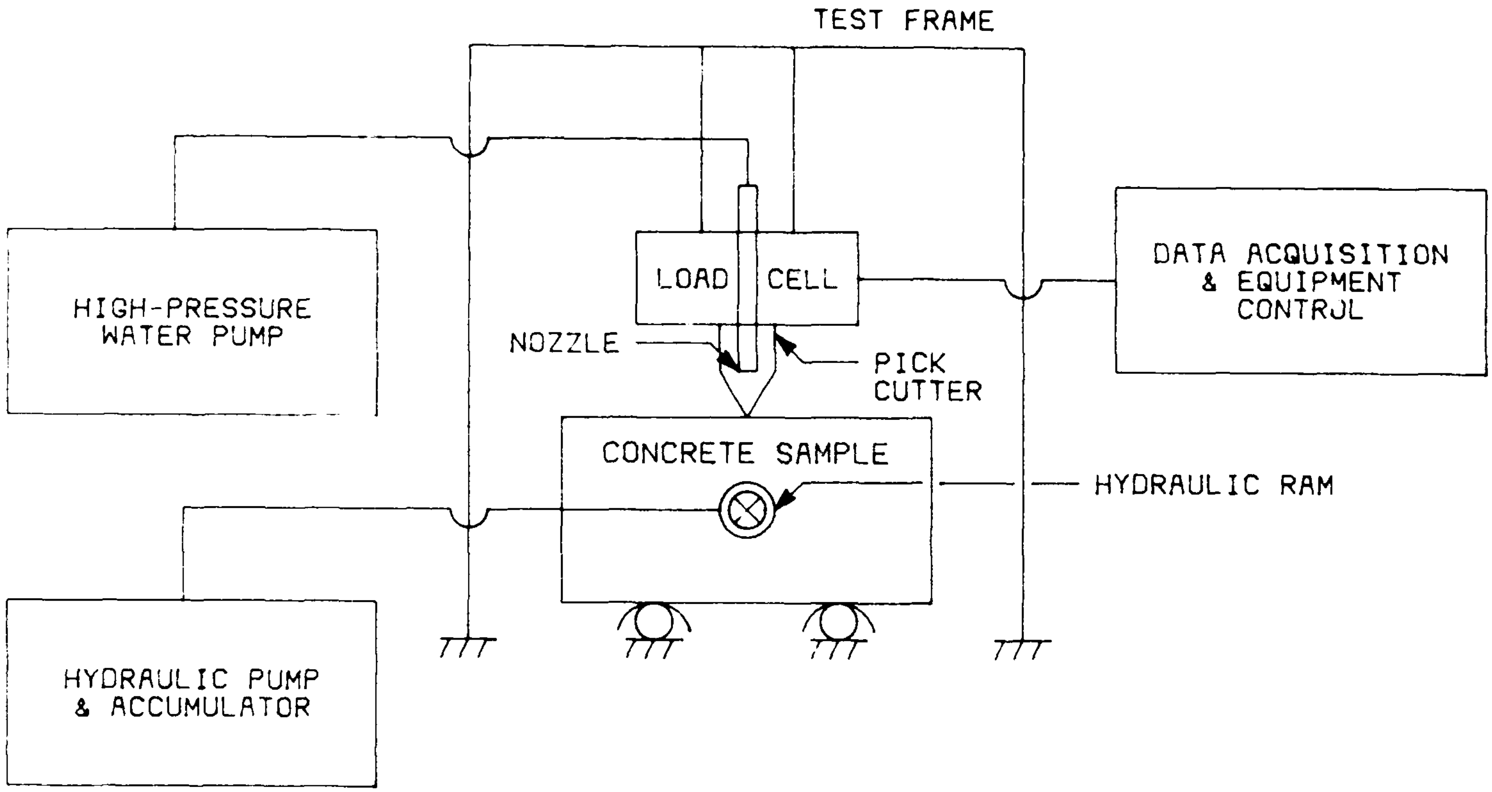


Figure A-2-1. Equipment and Instrumentation Schematics (View Along Cutting Axis).

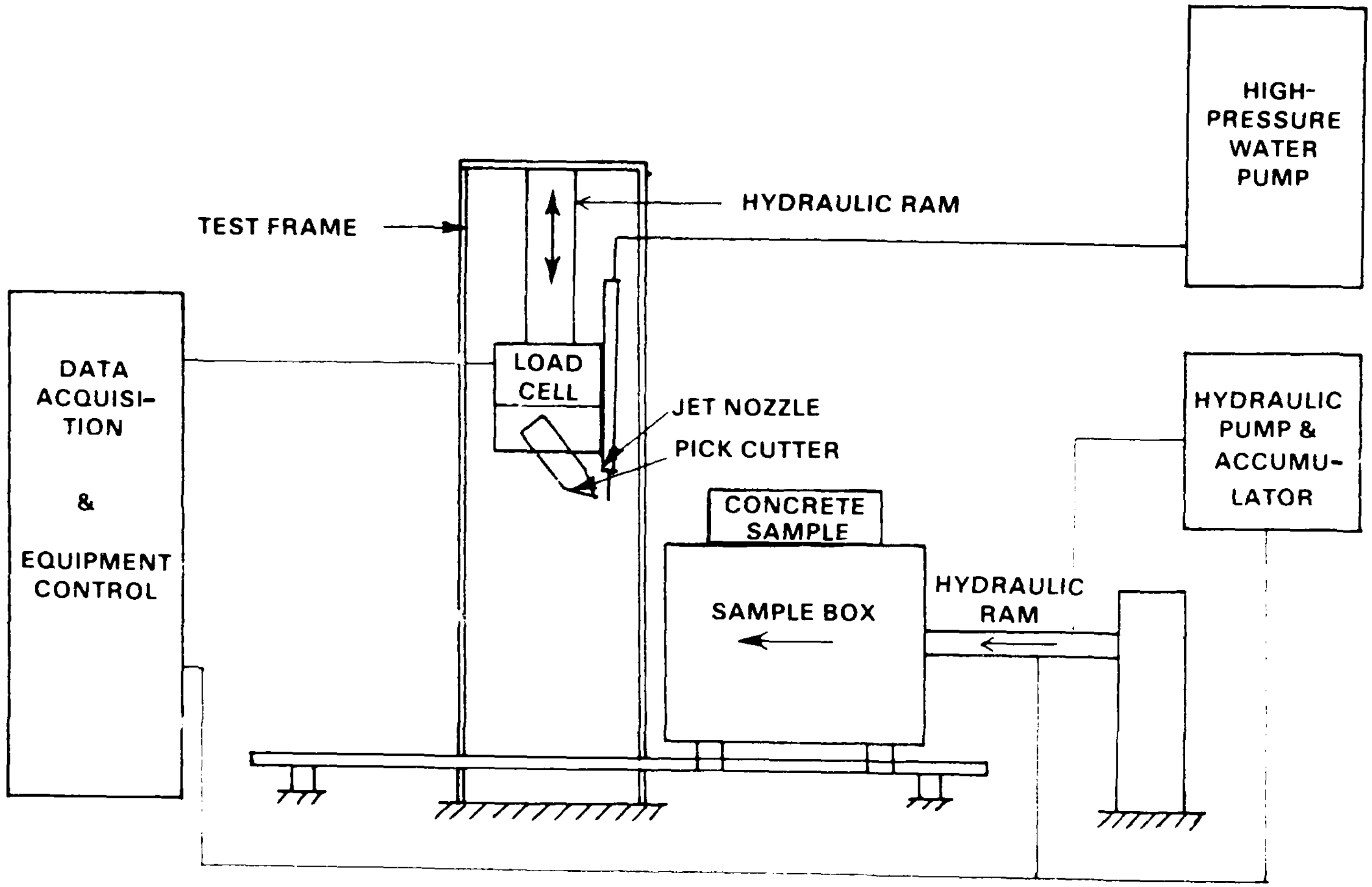


Figure A-2-2. Equipment and Instrumentation Schematics (Side View).

raised or lowered by a hydraulic ram mounted to the top of the beams. Steel plate spacers are placed between the cutter mounting and the cross-beam so that a constant cutter height could be maintained. Calibration experiments showed that a 25,000-pound load on the cutter produced less than 0.01 inch deflection on the frame. The sample box, fabricated from I-beams, is positioned horizontally beneath the cutter and moves horizontally on two 3-inch diameter steel rails anchored to the floor. Four linear bearings provide a rigid, low-friction mount.

Horizontal thrust is provided by a servo-controlled hydraulic ram that can provide 30,000 pounds of force at a 40-inch per second feed rate over a 5-foot stroke. To index the cutting paths, a pair of 2-foot stroke, double-acting cylinders movesthe concrete holder box sideways.

c. Force Monitoring System

This unit consists of signal conditioners and a digital integrator that determines the average values for the normal, drag, and side forces on the cutter. The triaxial load cell consists of two thick aluminum plates separated by four prestressed, hollow aluminum cylinders on whose circumferences are mounted six dual-element strain gages. The gages are wired into three full bridge circuits, one for each principal load direction. Calibration tests show less than 2 percent cross-talk between the circuits. For the planned tests, the drag bit is to be mounted with its cutting points in a vertical plane passing through the center line of the load cell so that the thrust force on the bits is purely compressive. The side and drag forces on the bits produce moments on the load cell about two orthogonal axes. Strain gage excitation and signal amplification is provided by three separate signal conditioners. A steady 10 volt input is supplied to each bridge. The output from each bridge is channeled through a 100-2,000 variable gain amplifier. The amplified signals are digitized at 1,000 readings per second, and an integrator sums the digital values and provides a four-digit readout for the total force per cut for each channel. These digitized values are divided by the elapsed time per cut to give the average force. Peak force values during the cut are also obtained. A microswitch located on the thrust ram is adjusted for the particular cut length, and controls the integration circuits.

d. Waterjet System

This unit consists of a high-pressure pump, a pressure regulator, and a nozzle assembly. The pump is a commercially available unit.

A Hydroblaster Model 610 pump with lower (4.5 gpm) flow is to be used for the planned tests. The unit consists of a small six-cylinder axial piston pump powered by a 20-horsepower electric motor. The constant displacement output could produce up to 12,000 psi pressure. A 0.5-inch diameter steel braided hose connects the pump to the nozzle.

The pressure regulator consists of a screw-controlled compression spring, forcing a needle into the orifice of a tee coupling. Changing the spring force regulates the quantity of flow allowed to bypass the needle. A second needle valve in the delivery line controls the flow to the nozzle.

5. SPECIFICATION OF CONCRETE TEST SAMPLE

The specifications of the concrete test samples are listed in Table A-2-1.

6. SCHEDULE

a. Equipment Setup and Calibration: June 28 to July 3, 1982.

b. Waterjet Kerfing Test: July 5-6, 1982.

c. Mechanical Concrete Cutting Test: July 7-9, 1982.

d. Waterjet-Assisted Mechanical Concrete Cutting Test: July 12-16, 1982.

APPENDIX B

ABRASIVE WATERJET CONCRETE CUTTING

APPENDIX B

ABRASIVE WATERJET CONCRETE CUTTING

The material in this appendix was prepared by the Fluidyne Corporation, 28 37th Street N.E., Auburn, Washington, 98002 under subcontract to The BDM Corporation between March 1982 and January 1983.

1. INTRODUCTION

a. Background

(1) Waterjet Technology. High-pressure waterjets have been evaluated for cutting rock and minerals. In such applications, a rock's compressive strength and permeability have significant influence on the performance of waterjet. It has been observed that there exists a threshold water pressure for a given rock below which the waterjet cannot cut the rock within a practical dwelling time. Typical values of such threshold pressure are 5,000 psi for sandstones and 15,000 psi for granite. To achieve practical cutting speed for rocks, water pressure considerably higher than the rock's threshold pressure is generally required. Cutting concrete with waterjets has similar pressure requirements due to the presence of hard aggregates. Therefore, most of the investigative work in cutting rock with waterjets involved a water pressure above 40,000 psi. To obtain such pressure levels, special pressure intensifiers must be used; such intensifiers have limited flow capacity and seal reliability, and are expensive.

Another important operating parameter of high-pressure waterjets is the nozzle standoff distance. Available test results have shown that a high-pressure waterjet's nozzle standoff distance in cutting hard materials is generally limited to a few inches. Thus, the target material must be placed very close to the nozzle, and to completely cut through the material it must be of a thickness well within the effective waterjet nozzle standoff distance.

The requirement of very high water pressure and the limited effective nozzle standoff distance are two major factors that prevented the use of high-pressure waterjets in practical applications such as cutting and drilling concrete, hard rock and minerals.

(2) Abrasive Waterjet Technology. The capability of a waterjet in cutting rock and other hard materials can be significantly improved if abrasive particles are incorporated into the jet stream. However, implementing this concept requires a suitable process and equipment, particularly nozzles that can withstand the erosion and wear encountered. Fluidyne has developed unique nozzles (patent-pending) that allow selected abrasives to be introduced into the water stream after the jet orifice.

Therefore, the jet orifice is not subject to the abrasive distress, yielding a long, usable lifetime. The nozzle utilizes multiple orifices, suitably arranged to generate strong suction and mixing actions to entrain the abrasives into the coherent jet streams. A secondary nozzle made of wear-resistant material is utilized to create a mixing chamber inside the nozzle. The multiple jets are arranged in parallel or in a converging pattern to generate abrasive waterjets of different widths and cutting capabilities.

Since Fluidyne's nozzle utilizes high-quality sapphire or ruby orifices, the quality and coherence of the waterjet are maintained. A circular arrangement of the jets provides a central zone for entraining the abrasives and the natural dispersion of the jets ensures the entrainment of abrasive particles into the jet stream. The secondary flow-shaping cone is sized according to the diameter of the jet bundle, thus ensuring the generation of a strong vacuum (28 to 30 inches Hg) inside the nozzle; such strong suction allows abrasive power to be fed to a nozzle without the need for compressed air. In addition, the multiple jets shield the surface of the throat of the flow-shaping cone from the abrasives, thus minimizing the wear of the cone. With such a nozzle, an abrasive waterjet of high capabilities can be generated at relatively low water pressures. Thus, commonly available pump systems could be used to cut concrete and hard rock.

2. LITERATURE/TECHNICAL REVIEW

a. Current State of Abrasive Waterjet

(1) British Hydromechanics Research Association (BHRA). BHRA is known to have engaged in the research and development of abrasive waterjet technology for some time (References B-1, B-2 and B-3). According to published papers, it appears that BHRA utilizes a jet-pump principle to entrain abrasives into a waterjet. The BHRA jetting head appears to have two nozzles, an upper waterjet nozzle and a lower slurry nozzle, that form a mixing chamber. The abrasives can be either dry or slurry, indicating that a negative pressure is generated in the mixing chamber. Apparently, the abrasive slurry is used primarily for the purpose of minimizing spark potential in cutting steel under hazardous conditions. Otherwise, dry abrasives such as copper slag, sand and silicon carbide, could be used. The pump system that BHRA used in its investigations is believed to be a triplex crankshaft pump commonly used in jet cleaning and blasting applications; such pumps are capable of peak water pressure of 20,000 psi with a flow capacity (power output) possibly in excess of 20 gpm. Most of BHRA's abrasive waterjet work was performed at a water pressure in the range of 10,000 to 14,000 psi, and a flow rate of about 12 gpm, with an abrasive (copper slag) feed rate of 12 pounds/minute. The waterjet nozzle was reported to be 1.8 mm (0.07 inch) in diameter. However, the diameter of the secondary nozzle was not reported. The cut made on concrete by this abrasive waterjet appeared to be about 1.0 to 1.5 inches in width. Thus, the exit diameter of the secondary nozzle of BHRA's jetting head may range between 0.25 to 0.50 inches.

Since the cut made by BHRA's abrasive waterjet is quite wide, it is not clear if some of the aggregates are not simply washed away by the jet. However, the ability of copper slag to cut through steel reinforcing rods indicates that the abrasive is quite hard and thus can abrade aggregate. The published data indicate that a depth of cut of 4 inches can be achieved if the nozzle is traversed at a speed of 1 inch/minute. Four passes of the jet cut through a 16-inch thick concrete block. These data show that a 4-inch deep cut requires a jet exposure time of about 15 seconds if the jet diameter at the nozzle exit is assumed to be about 0.25 inch. Thus, if the nozzle is traversed at much higher speed, such as 2 inch/minute, the depth of cut is expected to be reduced to less than 1 inch.

(2) Flow Industries, Inc. Flow Industries, Inc., (Flow) is also known to be involved in abrasive waterjet work, as demonstrated by two papers presented in the 6th International Symposium on Jet Cutting Technology (References B-4 and B-5). Flow's work looks at cutting materials at water pressure in the range of 30,000 to 40,000 psi. Thus, it appears that high-pressure intensifiers were employed.

The published papers did not report the design of the nozzle that Flow used in its work. However, the orifice diameter was cited throughout the two papers. Thus, it is believed that Flow's nozzle is basically similar to that used by BHRA, involving a waterjet nozzle that is coupled to a slurry nozzle with a mixing chamber in between. BHRA used a waterjet nozzle of 1.8 mm (0.07 inch) in its concrete cutting work while Flow used a 0.635 mm (0.025-inch) waterjet nozzle because of its much higher pressure. Flow's work involved the use of dry abrasive powder (garnet) in quantities slightly less than that used by BHRA.

Flow's published data show that its abrasive jet can cut concrete to a depth of about 5 inches in one pass at 35,000 psi water pressure, 9.3 pound/minute abrasive feed rate, and 6 inches/minute nozzle traverse speed. Increasing the nozzle traverse speed to 9 inches/minute, the depth of cut was reduced to about 2 inches. Reducing the water pressure to 15,000 psi, the depth of cut at 9 inches/minute nozzle traverse would have been reduced to about 1.3 inches. These figures could be considered as Flow's baseline data, which are more favorable than BHRA's concrete cutting data because of the higher water pressure involved.

(3) Major Unknowns. Both BHRA and Flow publicly report little data about the nozzle design and performance, with no data about the life of the secondary nozzle. In general slurry nozzles are subjected to substantial wear at high abrasive feed rates. Further, the performance of the abrasive jet can deteriorate as the bore of the slurry nozzle increases. Once the bore is increased, abrasives will be escaping through the space around the jet and thus wasted. A method of reducing this problem is to employ a long slurry nozzle. In addition, long slurry nozzles are also needed to entrain abrasives into a single waterjet. Fluidyne's abrasive waterjet nozzles do not have such limitations. Thus, the entrainment of

abrasives is better and the wear of the secondary nozzle is significantly reduced. Further, the amount of vacuum generated inside Fluidyne's nozzle is appreciable and can be maintained at a constant level for a long period of time. These differences explain why Fluidyne has been able to cut concrete with its abrasive waterjet faster than both BHRA and Flow under similar operating conditions. However, questions on its ultimate capabilities still remain as nozzle optimization has not yet been completed.

b. Design Parameters

A basic abrasive waterjet system consists of certain major system components, namely the pump unit, abrasive feed system, and the nozzle system. If the system pressure is limited to 20,000 psi, there are commercially available crankshaft pumps of a wide range of power outputs. If a system pressure greater than 20,000 psi is involved, intensifiers must be used and the selection of suitable pumps is restricted. Still, intensifier pumps of large power output are commercially available. Abrasive feed systems are commercially available for sandblasting applications and with minor changes these systems are suitable for generating an abrasive waterjet. Thus, the center of attention of abrasive waterjet systems is the nozzle system, which basically determines how the available power is transferred to the water and abrasive particles, and how they are coupled to the target material. The wear problem is also most severe at the nozzle as the abrasive particles are traveling at high speed both within and outside the nozzle.

The exact mechanism involved in cutting materials with abrasive waterjet is believed to be very complex because of the high-speed, multiple phases involved. It is not known at present how the abrasives are distributed in the waterjet and how fast they are traveling. It is easy to see, however, that abrasives must be entrained into the waterjet if the resultant abrasive waterjet is to have high cutting capability. Once entrained, the speed of abrasive particles obviously would have influence on the capability of the abrasive waterjet. Since the maximum speed that abrasive particles can attain is the speed of waterjet, the water pressure is, therefore, influential. The relationship between the water pressure and the waterjet speed can be approximated by Bernoulli's equation for incompressible flow:

$$v = (2P/\rho)^{1/2}$$

where v = waterjet speed

P = static water pressure

ρ = density of fluid.

Thus, the basic design criterion of abrasive waterjet nozzles is to maximize abrasive entrainment and to minimize wear; the water pressure is of

secondary concern as changes of the pump system will bring about the desired pressure. The entrainment of abrasive and the desire to maintain waterjet coherence are basically countering each other. Fluidyne's nozzle design is based on a compromise such that the natural dispersion of a coherent waterjet is utilized for entraining abrasives. To best utilize this approach, multiple waterjets encircle an abrasive core so that the waterjets completely envelop the abrasive particles and force them to enter into the converged jet stream resulting from the jet dispersion. Thus, the arrangements of the orifices, size of orifices, and the opening of the secondary nozzle are important factors of optimum abrasive entrainment. Once these factors are decided, there will be a maximum abrasive flow rate beyond which choked flow will occur. However, this maximum abrasive flow rate may not be the optimum abrasive flow rate for cutting a given material. The type of abrasive, too, will have impact on cutting concrete as the abrasive waterjet must overcome numerous types of aggregates.

3. TEST DATA ANALYSIS

a. Summary of Results

(1) Jet Configurations. In this project, seven orifice configurations were made available for testing. These seven orifice configurations are:

(a) Parallel Jets - 1, 3, 4, 5, and 6 jets

(b) Converged Jets - 5 and 6 jets.

Therefore, seven orifice cones were neded and fabricated for testing at 15,000 psi water pressure. Additional orifice cones were also made available for testing at other pressure levels.

Initial testing quickly showed that 5- and 6-jet orifice cones are superior to others in the entrainment of abrasives and in cutting test concrete specimens. Thus, 1-, 3-, and 4-jet orifice cones were not tested further. In addition, the 5-parallel-jet orifice cone, because of the closer pack of the jets, exhibited slightly better cut depth than the 6-parallel-jet orifice cone. Thus, most of the tests were conducted with the 5-parallel-jet nozzle.

The convergent-jet orifice cones were not tested extensively because of the absence of optimum flow-shaping cones. It was observed, however, that both 5- and 6-converged-jet orifice cones are capable of cutting concrete to a depth comparable to that produced by the 5-parallel-jet cone even though optimum flow-shaping cones were not available. Generally, the cuts made by the converged-jet nozzles are narrower and could be made at reduced abrasive consumption. Thus, these converged-jet orifice cones could be useful in an overall deep-slotting scheme for cutting through concrete slabs.

Most of the tests were performed in this project at 15,000 psi water pressure and with the 5-parallel-jet orifice cone, using five 23 mil orifices. For testing at 12,000 psi and 17,000 psi water pressure, 26 and 22 mil orifices were employed, respectively. For the 6-parallel-jet orifice cones, orifices of different sizes were used.

(2) Effect of Concrete Types. Most of the cutting tests performed in this project were with concrete specimens cast by the Concrete Technology Corporation (CTC) of Tacoma, Washington; a total of 20 pieces of 16- by 16- by 8-inch specimens were made. These specimens were cast according to BDM's specifications except that locally available Steilacoom aggregates (a mixture of 6 to 7 kinds of small igneous rock of about 0.5 inch diameter) were used. According to CTC, these aggregates are very hard and the compressive strength of these concrete specimens could reach 10,000 psi after some time.

A 24- by 24- by 30-inch concrete block was also obtained from the Columbus Cement Products Company of Columbus, Ohio. This block was cast according to BDM's specifications and contains crushed Georgian mountain granite aggregates. Concrete of the same specifications was used in cutting tests of diamond saws and the waterjet-assisted mechanical cutting system (Appendix C).

Test results show that the Columbus concrete is much easier to cut with Fluidyne's abrasive waterjet than the Tacoma concrete; the difference in depth could be more than 100 percent under certain conditions. It is concluded that the hardness and resistance to abrasion of the aggregates caused the difference. The mountain stone granite aggregate not only appeared to be slightly softer but it also had a coarser grain size and texture than the Steilacoom river rock aggregate.

Since crushed limestone, another aggregate used in concrete and limestone, is generally softer than granite, the Columbus concrete could be considered as an "average" concrete. Thus, it is not unreasonable to expect that Fluidyne's abrasive waterjet could cut some types of concrete even faster than its performance with the Columbus concrete. However, whether the cutting rate can meet RRR specifications is another matter.

(3) Effect of Abrasives. The type of abrasives, grain size, and feed rate all affected the capability of abrasive waterjet. For cutting concrete containing hard aggregates, hard abrasives such as garnet are recommended. When the concrete contains softer aggregates, softer abrasives, such as sand, become feasible. If sand is used as abrasive, the shape of sand grains affects the jet performance; sharp-edged sand is preferred over rounded-out beach sand.

For cutting the Tacoma concrete specimens, garnet (Idaho) was found to be superior than silica sand (Nevada) and Green Diamond abrasive (Texas mineral). With garnet as abrasive, larger grains are more

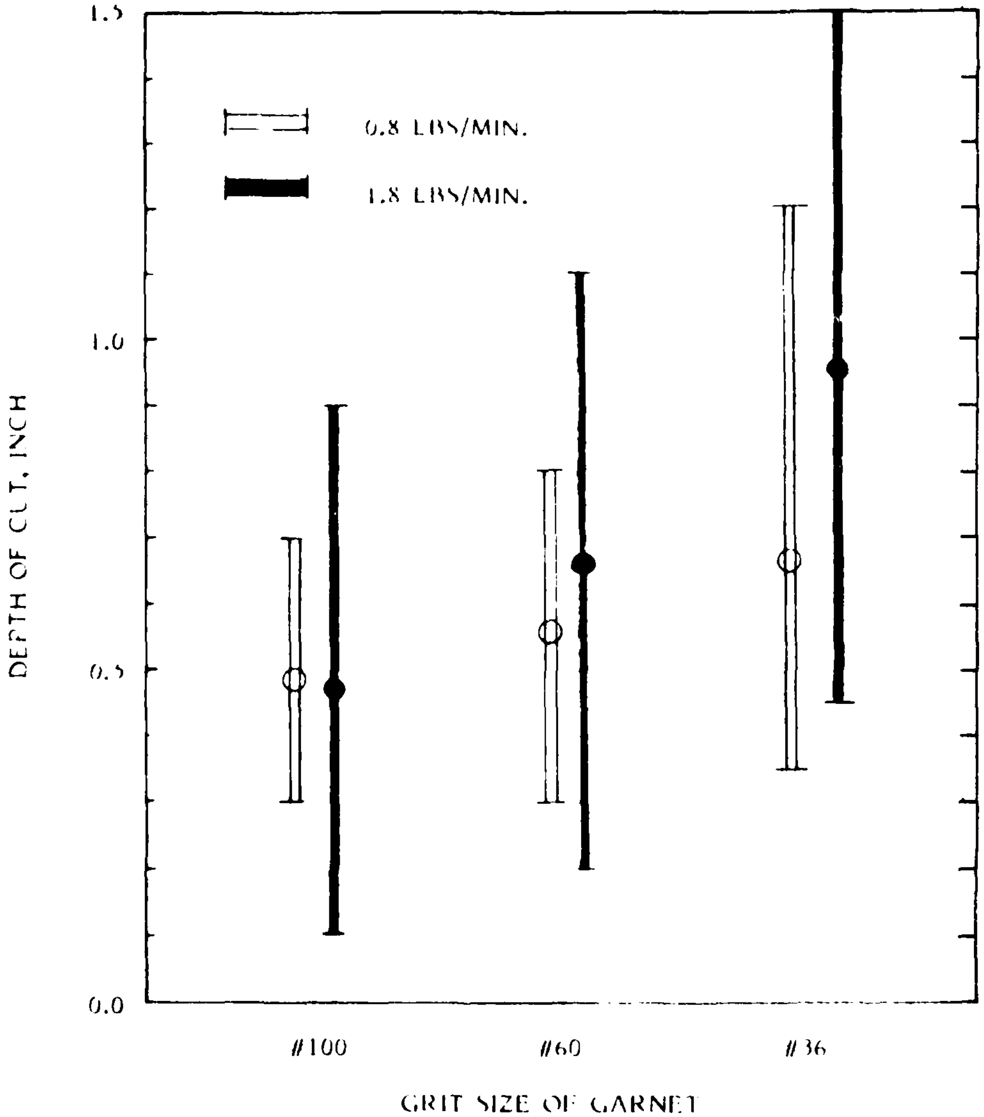
effective than finer grains (Figure B-1). Thus, garnet of grit size No. 36 was selected for most of the tests.

The performance of abrasive waterjet was found to improve as the abrasive feed rate was increased (Figure B-2). However, the benefit of increased abrasive flow leveled off after the abrasive feed rate reached a certain point. It is believed that the optimum abrasive feed rate is related to factors such as orifice configuration, power input, nozzle traverse speed, and concrete type. In this project, most of the tests were performed at a garnet feed rate of 1 to 3 pound/minute, which is considerably less than that involved in BHRA's and Flow's work (Reference B-4, B-2). Additional experiments and analysis are required to optimize the abrasive feed rate.

(4) Nozzle Standoff Distance. The tests performed in this project have shown that the nozzle standoff distance does not play any prominent role in abrasive waterjet cutting of concrete as it does in high-pressure waterjet cutting of materials (Figure B-3). No noticeable difference in cut depth on Tacoma concrete was observed when the initial nozzle standoff distance was varied from 0.2 inch to 1.2 inch. Multiple-pass cutting also showed that Fluidyne's abrasive waterjet can continue to cut the granite aggregates in the Columbus concrete after the nozzle standoff distance has reached 22 inches. However, the initial nozzle standoff distance does affect the width and edge quality of the cut and therefore should be minimized. It is recommended that the nozzle should be in contact with the concrete surface in field applications and that the nozzle should be spring-loaded to maintain this contact, thus eliminating the need for any adjustment. However, wear-resistant materials, such as tungsten carbide, must be used for constructing the nozzle front end.

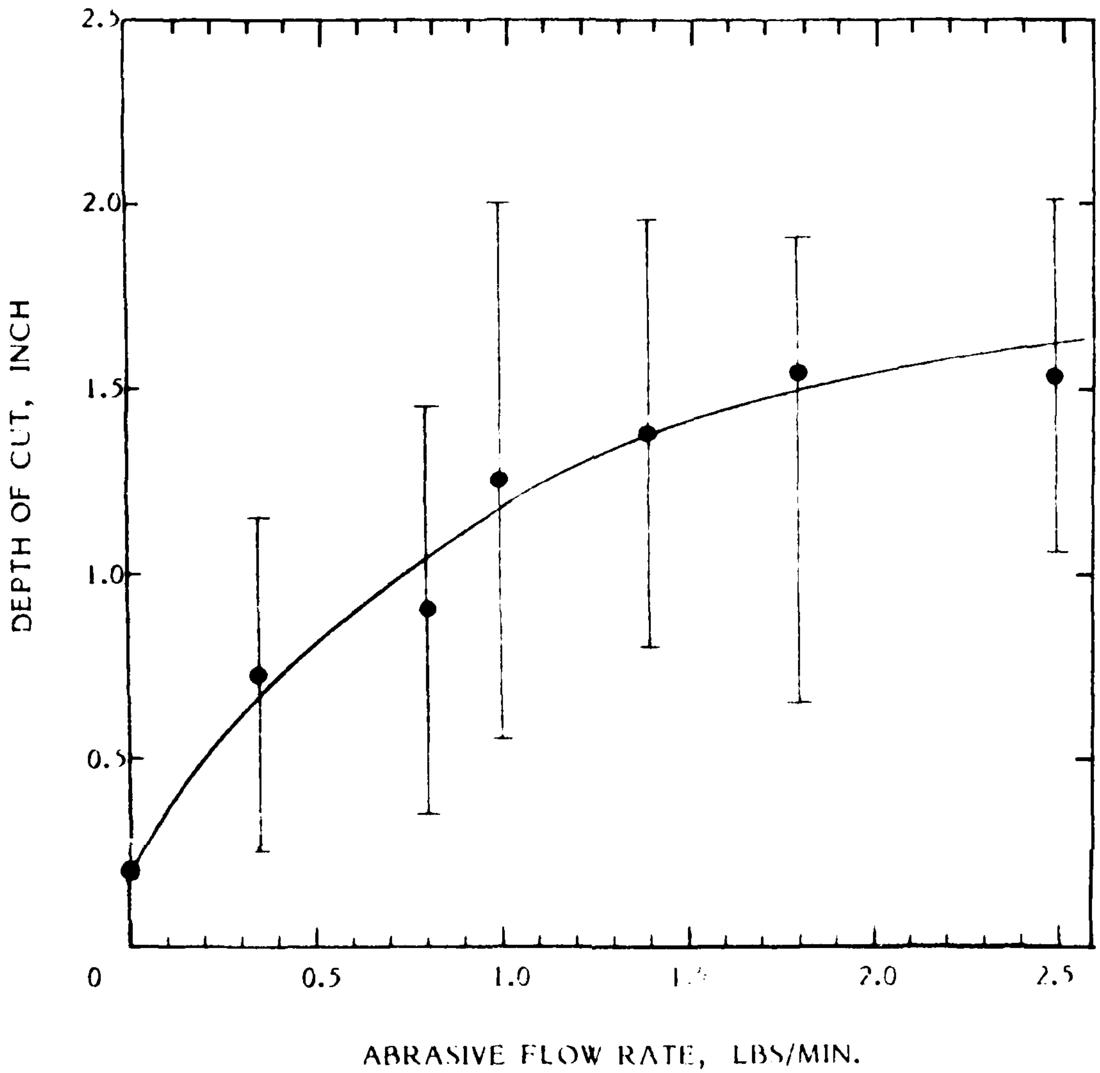
(5) Jet Impingement Angle. Because of the very hard aggregates found in the Tacoma concrete, the jet impingement angle can change the uniformity of the cut depth. However, no advantage in the overall depth of cut was found by changing the jet angle from 90 degrees to other positions (Figures B-4, B-5, and B-6). If the aggregates are softer, it may be advantageous to employ an angled abrasive waterjet because the jet impingement angle does change the contact time (or exposure time) between the abrasive waterjet and the target material. The extremely irregular depth produced by the abrasive waterjet on Tacoma concrete rendered accurate depth measurement very difficult; other errors involved in the cutting tests could easily cover depth deviations of ± 10 percent. Still, a trailing abrasive waterjet can produce a cut on concrete that is wider and has more uniform depth. Thus, the position of abrasive waterjet nozzle body could be a design factor for producing special cut features on concrete.

Figures B-7 through B-9 show the depth-of-cut profiles for a 30-degree off-normal leading jet, a normal incident jet, and a 30-degree off-normal trailing jet, respectively. Notice that as the jet varies from a leading to a trailing impingement angle the depth of cut profile becomes progressively smoother.



TEST SPECIMEN	Cast Concrete	TEST DATE	9-14-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	22 mils
WATER PRESSURE	15,000 PSI	FLOW RATE	5.5 - 6.0 GPM
ABRASIVE TYPE	Garnet Powder	FEED RATE	0.8 and 1.8 LBS/MIN.
TRAVERSE SPEED	20 feet/min.	NOZZLE STANDOFF	0.5 INCH
JET ANGLE	90°	NO. OF PASSES	1

Figure B-1. Effect of Abrasive Grit Size on Depth of Cut.



TEST SPECIMEN Cast Concrete

TEST DATE 9-14-82

ORIFICE CONE 5-Parallel-Jet

ORIFICE SIZE 22 mils

WATER PRESSURE 15,000 PSI

FLOW RATE 5.5 - 6.0 GPM

ABRASIVE TYPE Garnet Grit #36

FEED RATE ____ LBS/MIN.

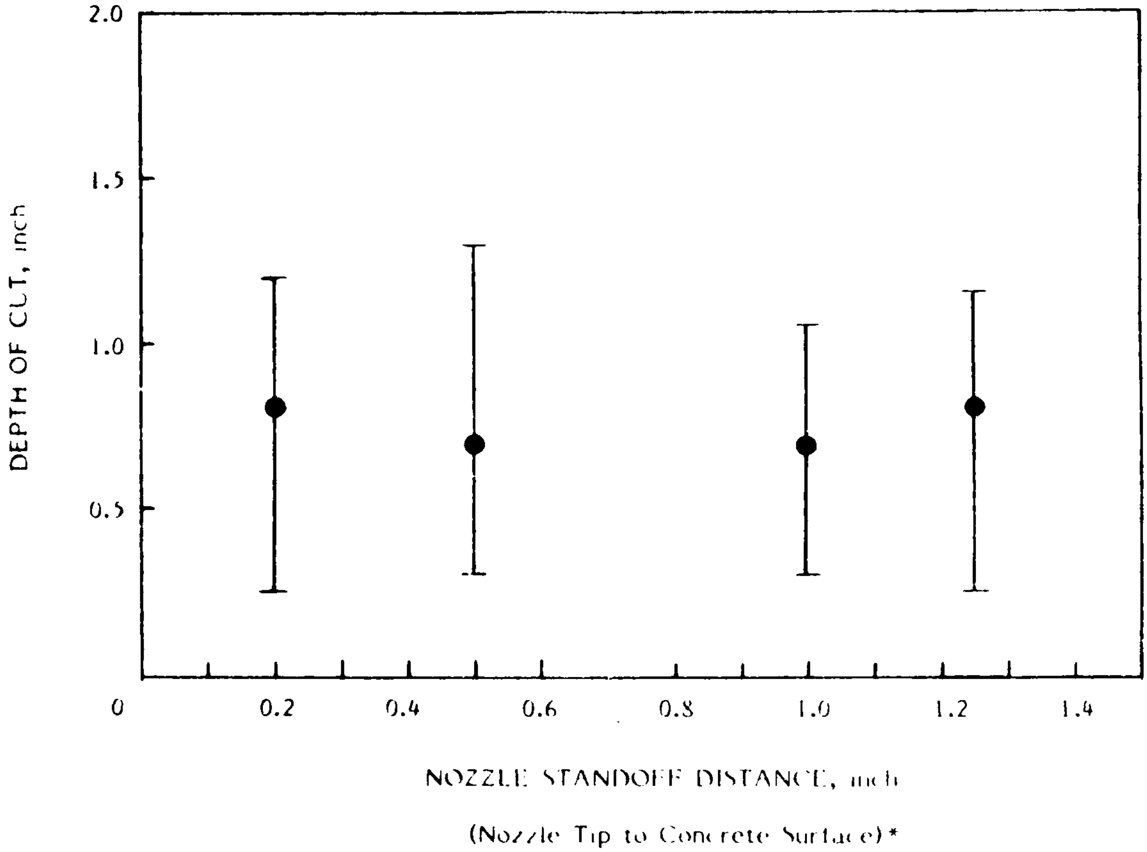
TRAVERSE SPEED 2.0 feet/min.

NOZZLE STANDOFF 0.5 INCH

JET ANGLE 90°

NO. OF PASSES 2

Figure B-2. Depth of Cut vs. Abrasive Flow Rate.



TEST SPECIMEN	Cast Concrete	TEST DATE	12-8-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	23 mils
WATER PRESSURE	15,000 PSI	FLOW RATE	5.8 GPM
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	1.8 LBS/MIN.
TRAVERSE SPEED	2.0 feet/min.	NOZZLE STANDOFF	INCH
JET ANGLE	90°	NO. OF PASSES	1

* Add 2.50 inch to obtain waterjet-orifice-to-surface nozzle standoff distance.

Figure B-3. Effect of Nozzle Standoff Distance on Depth of Cut.

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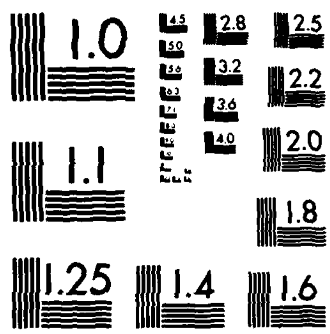

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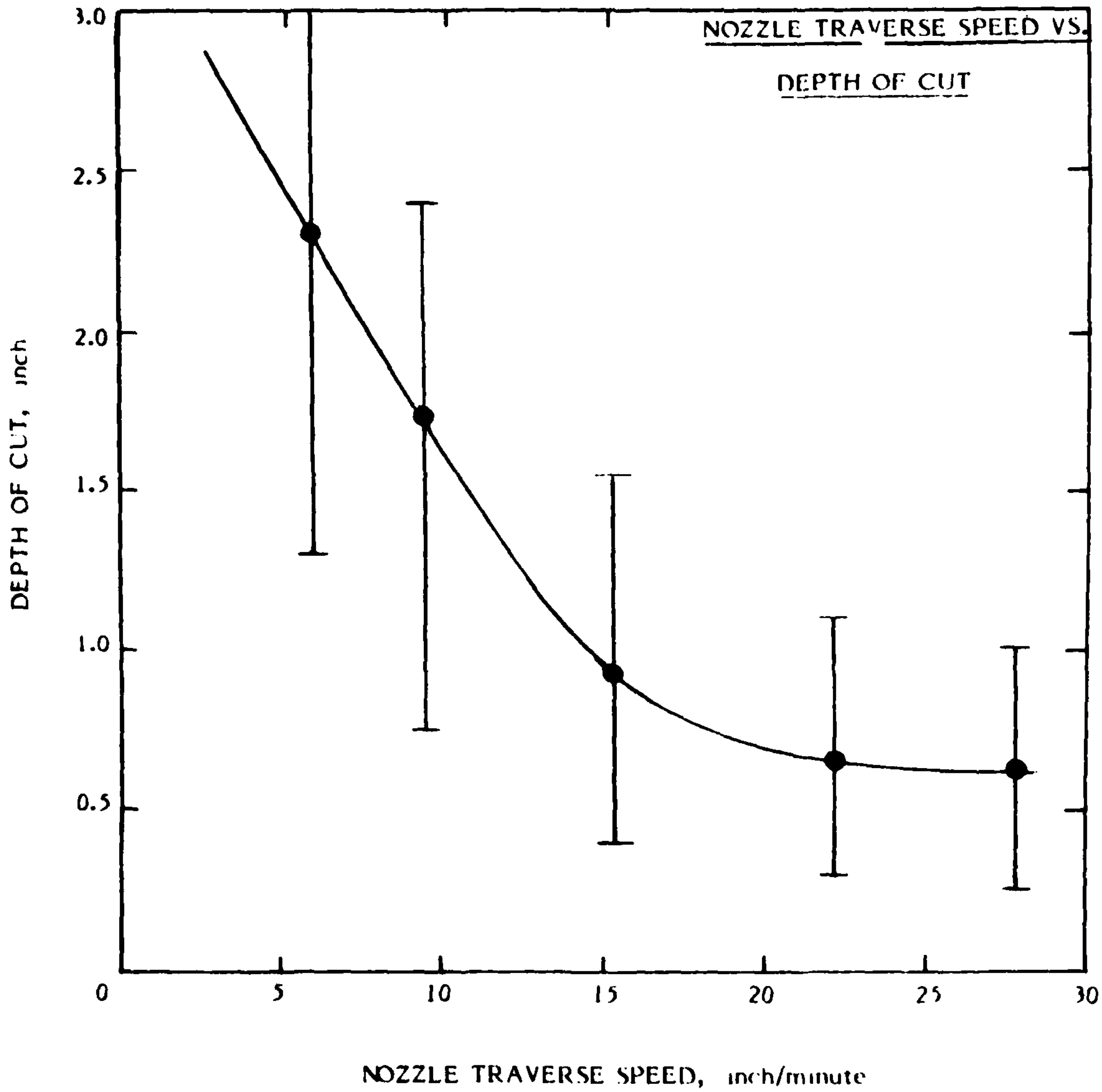
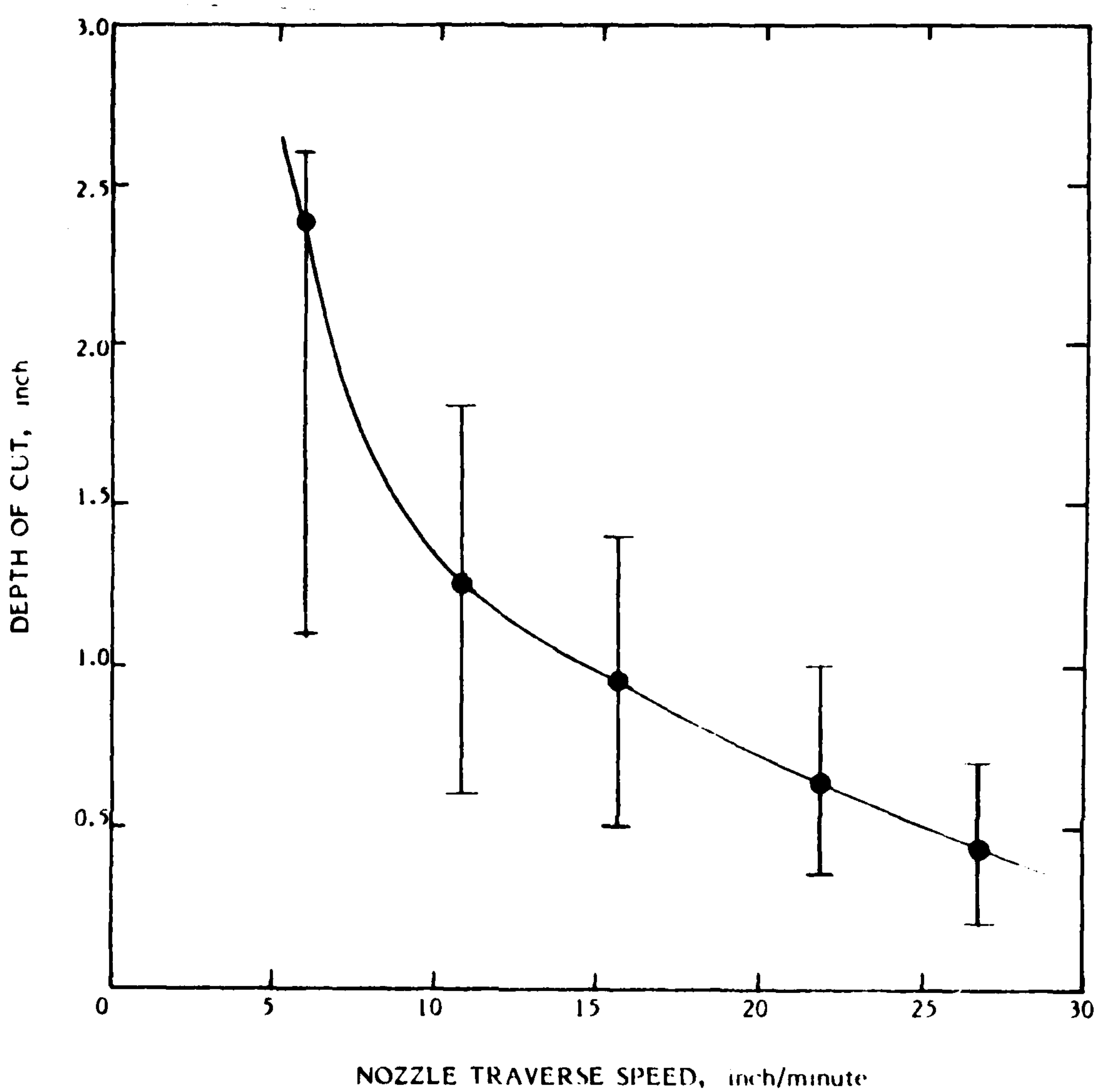


TEST SPECIMEN	Cast Concrete	TEST DATE	12-8-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	23 mils
WATER PRESSURE	15,000 PSI	FLOW RATE	5.8 GPM
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	1.8 LBS/MIN.
TRAVERSE SPEED		NOZZLE STANDOFF	0.25 INCH
JET ANGLE	90°	NO. OF PASSES	1

Figure B-4. Nozzle Traverse Speed vs. Depth of Cut.



TEST SPECIMEN Cast Concrete

TEST DATE 12-7-82

ORIFICE CONE 5-Parallel-Jet

ORIFICE SIZE 23 mils

WATER PRESSURE 15,000 PSI

FLOW RATE 5.8 GPM

ABRASIVE TYPE Garnet Grit #36

FEED RATE 1.8 LBS/MIN.

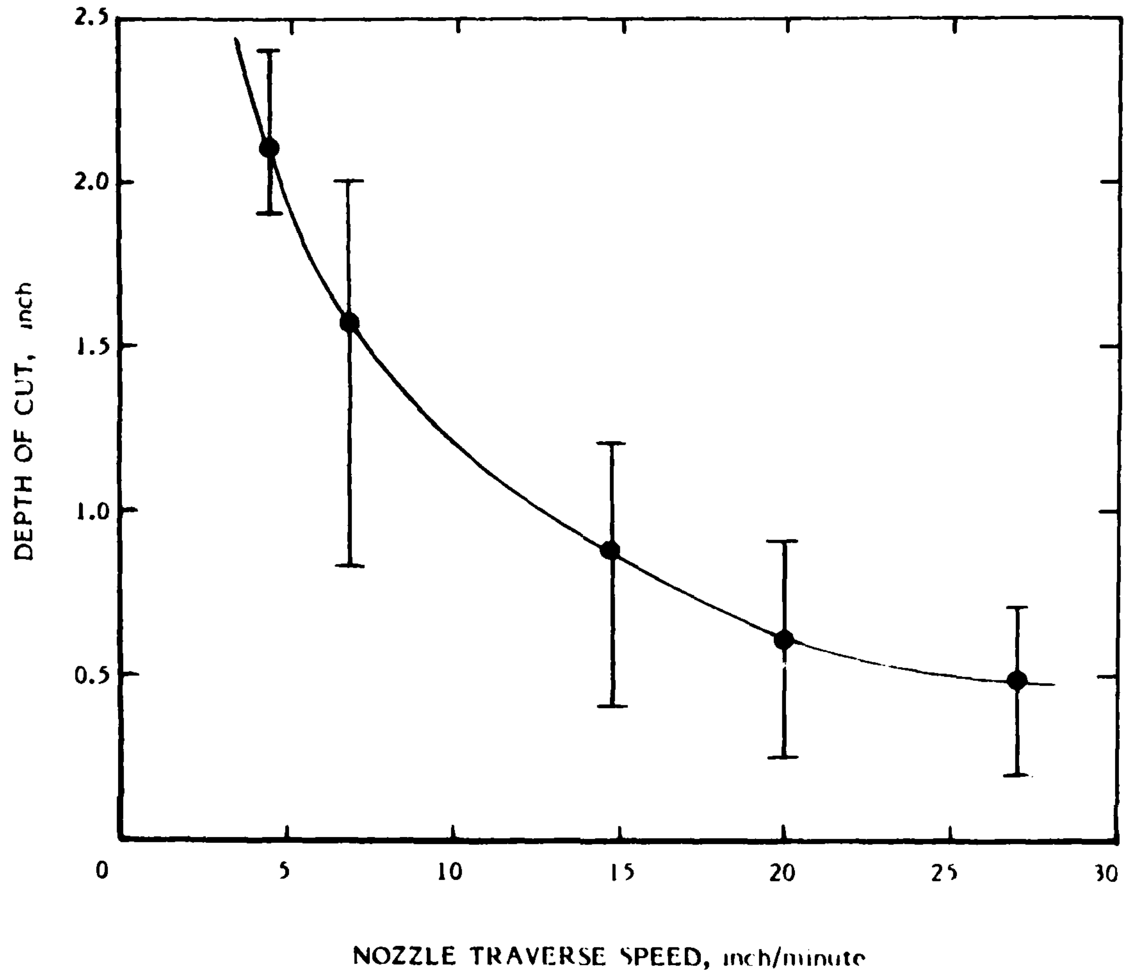
TRAVERSE SPEED

NOZZLE STANDOFF 0.25 INCH

JET ANGLE 30° Leading

NO. OF PASSES 1

Figure B-5. Effect of Jet Impingement Angle on Depth of Cut - 30 Degrees Leading.



TEST SPECIMEN Cast Concrete

TEST DATE 12-7-82

ORIFICE CONE 5-Parallel-Jet

ORIFICE SIZE 23 mils

WATER PRESSURE 15,000 PSI

FLOW RATE 5.8 GPM

ABRASIVE TYPE Garnet Grit #36

FEED RATE 1.8 LBS/MIN.

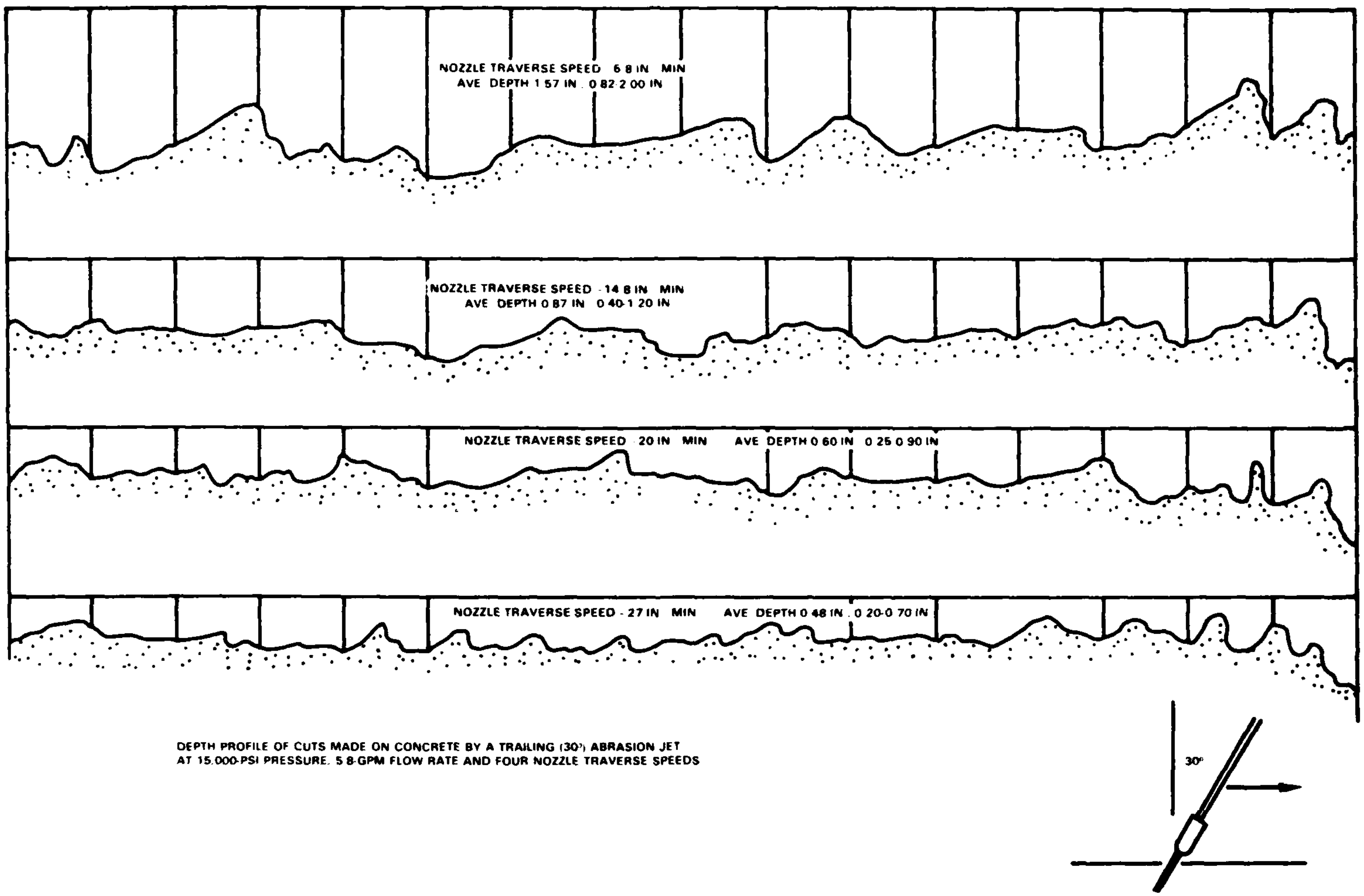
TRAVERSE SPEED

NOZZLE STANDOFF 0.25 INCH

JET ANGLE 30° Trailing

NO. OF PASSES 1

Figure B-6. Effect of Jet Impingement Angle on Depth of Cut - 30 Degrees Trailing.



DEPTH PROFILE OF CUTS MADE ON CONCRETE BY A TRAILING (30°) ABRASION JET AT 15,000-PSI PRESSURE, 5 8-GPM FLOW RATE AND FOUR NOZZLE TRAVERSE SPEEDS

Figure B-7. Trailing Jet Cutting Profile.

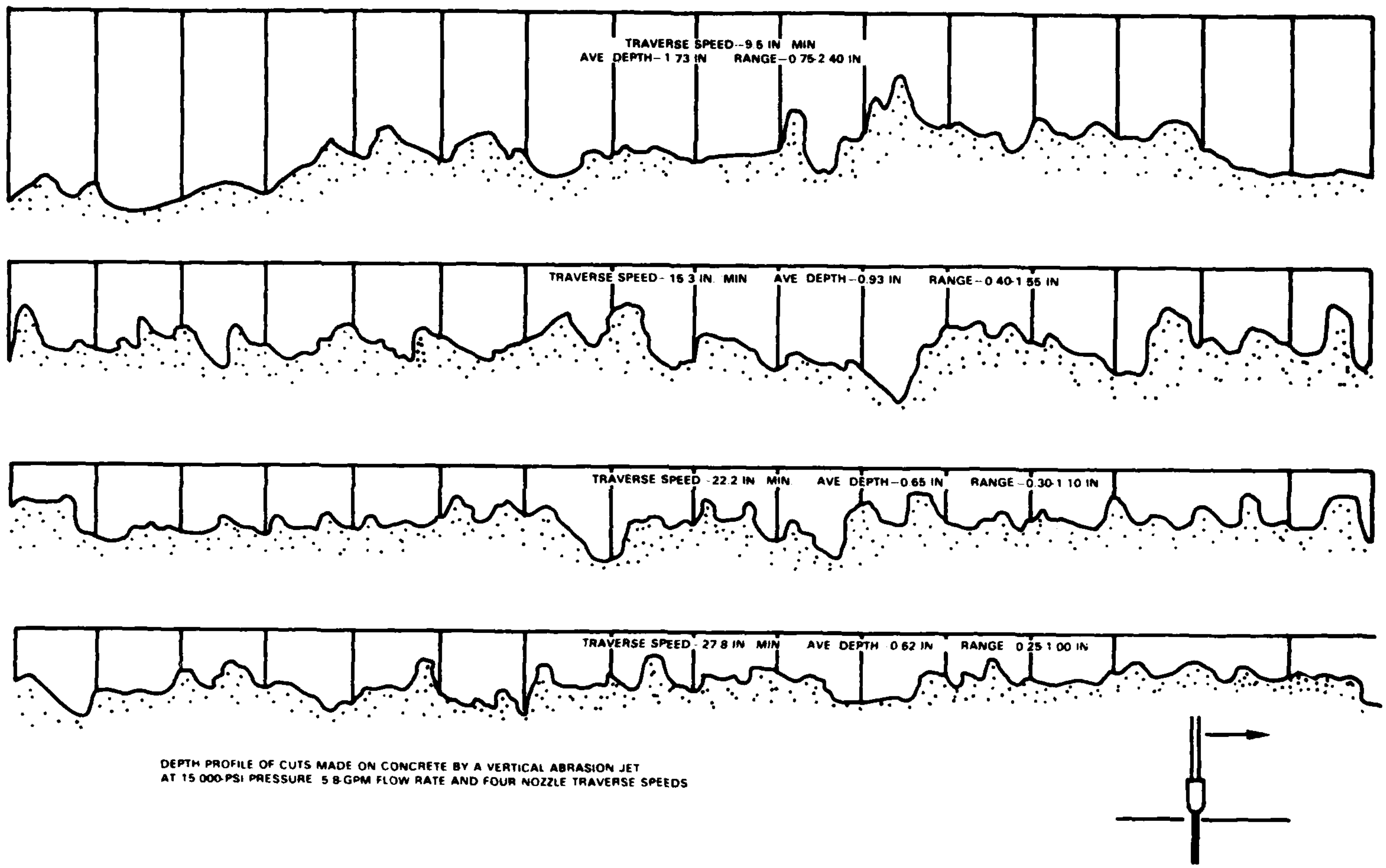


Figure B-8. Vertical Jet Cutting Profile.

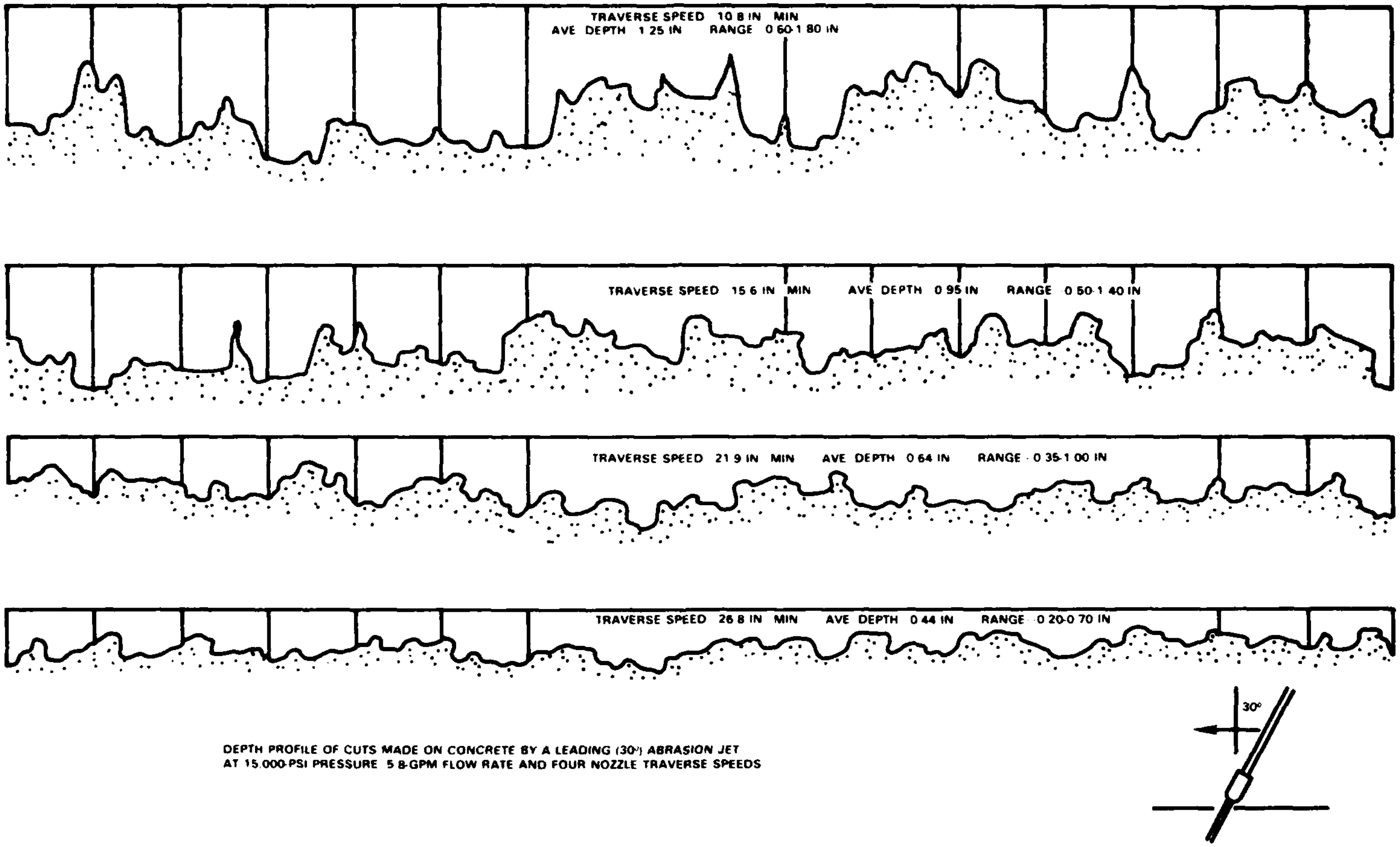


Figure B-9. Leading Jet Cutting Profile.

(6) Nozzle Traverse Speed. The speed at which an abrasive waterjet is moved over a concrete surface has a pronounced effect on the depth of cut; the depth of cut is increased significantly as the nozzle traverse speed is reduced beyond about 3 feet/minute (Figures B-10, B-11, and B-12). At traverse speed above this figure, the abrasive waterjet cannot be expected to cut all aggregates under the test conditions encountered in this project, unless multiple passes are applied.

The effect of multiple-traverse passes of an abrasive waterjet is approximately equivalent to cutting with multiple nozzles or cutting with a nozzle of multipled power output. With the hard Tacoma concrete, the 15,000 psi abrasive waterjet started to lose its cutting ability after the depth reached about 5 inches (Figure B-13). With the Columbus concrete, the 15,000 psi abrasive waterjet remained effective for much deeper cuts (Figures B-14, B-16, and B-17).

The effect of nozzle traverse speed and multiple-pass cutting on the depth of cut basically reflects the effect of the amount of time that concrete is exposed to abrasive waterjet, which could be called exposure time, T, and could be expressed by:

$$T = nd/v$$

where T = exposure time, seconds

n = number of passes

d = diameter of abrasive waterjet, inches

v = nozzle traverse speed, inches/second.

Plotting the exposure time versus depth of cut produces a parabolic curve (Figure B-18) that could be used to predict the depth of cut of a given concrete at any nozzle traverse speed. With the Columbus concrete, the plot shows that a 16-inch deep cut could be produced with Fluidyne's 15,000 psi abrasive waterjet in one pass if the nozzle is traversed at 1 inch/minute, as in the case of BHRA's work. On the other hand, BHRA's system produced a cut of about 4 inches in depth. However, specifications on the concrete BHRA was cutting are not available.

The available data at 15,000 psi using Fluidyne's abrasive waterjet system are compared to those published in Reference B-4 (Figure B-19). Differences in the abrasive feed rate should also be noted.

(7) Water Pressure. A limited range of water pressure was investigated in this project (Figures B-11, B-12, and B-15). However, the available data did show that increasing the water pressure (for a fixed pump horsepower and abrasive feed rate) increases the depth of cut significantly at all nozzle traverse speeds encountered in this project. The importance of water pressure is believed to be most significant with the

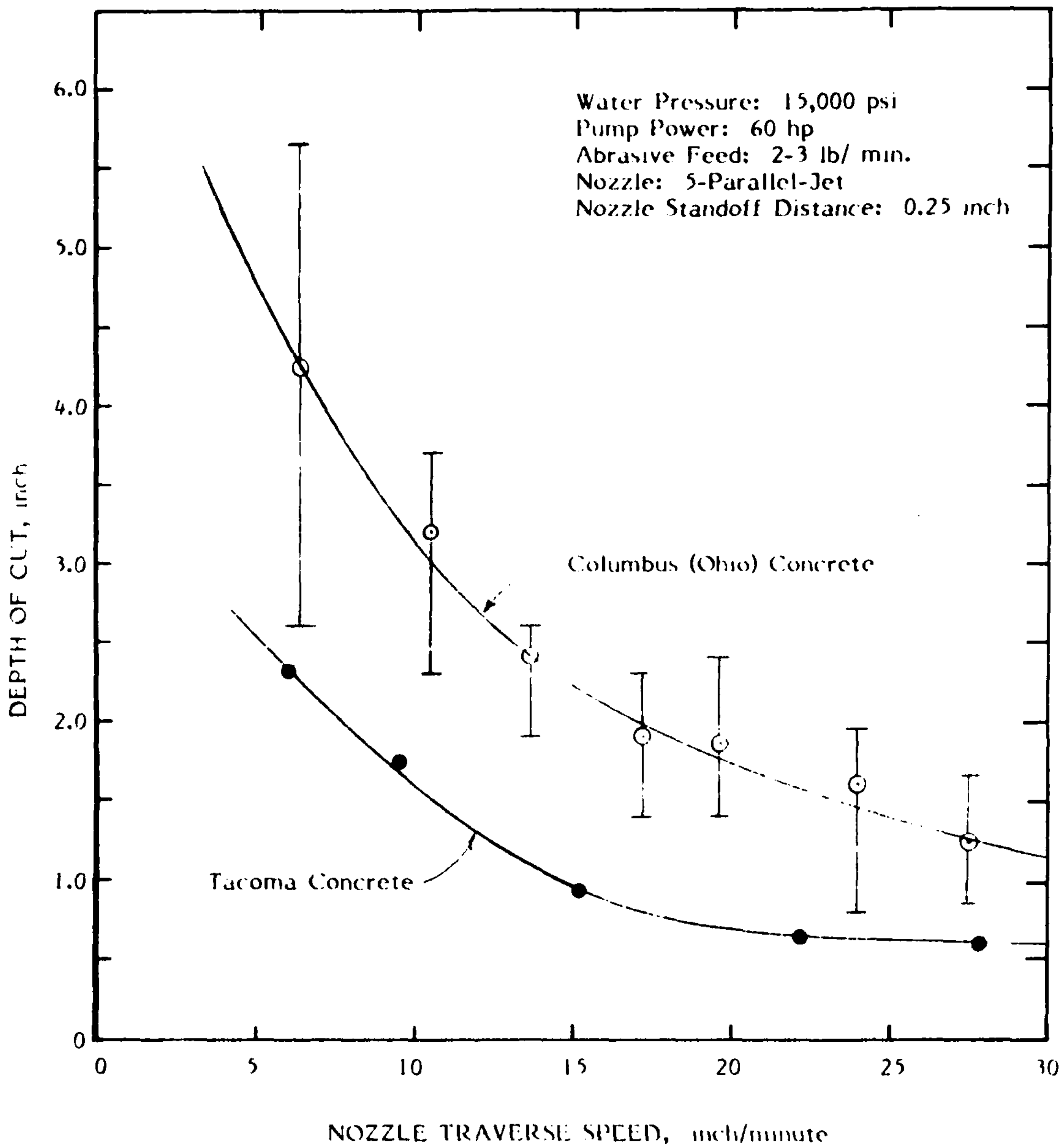
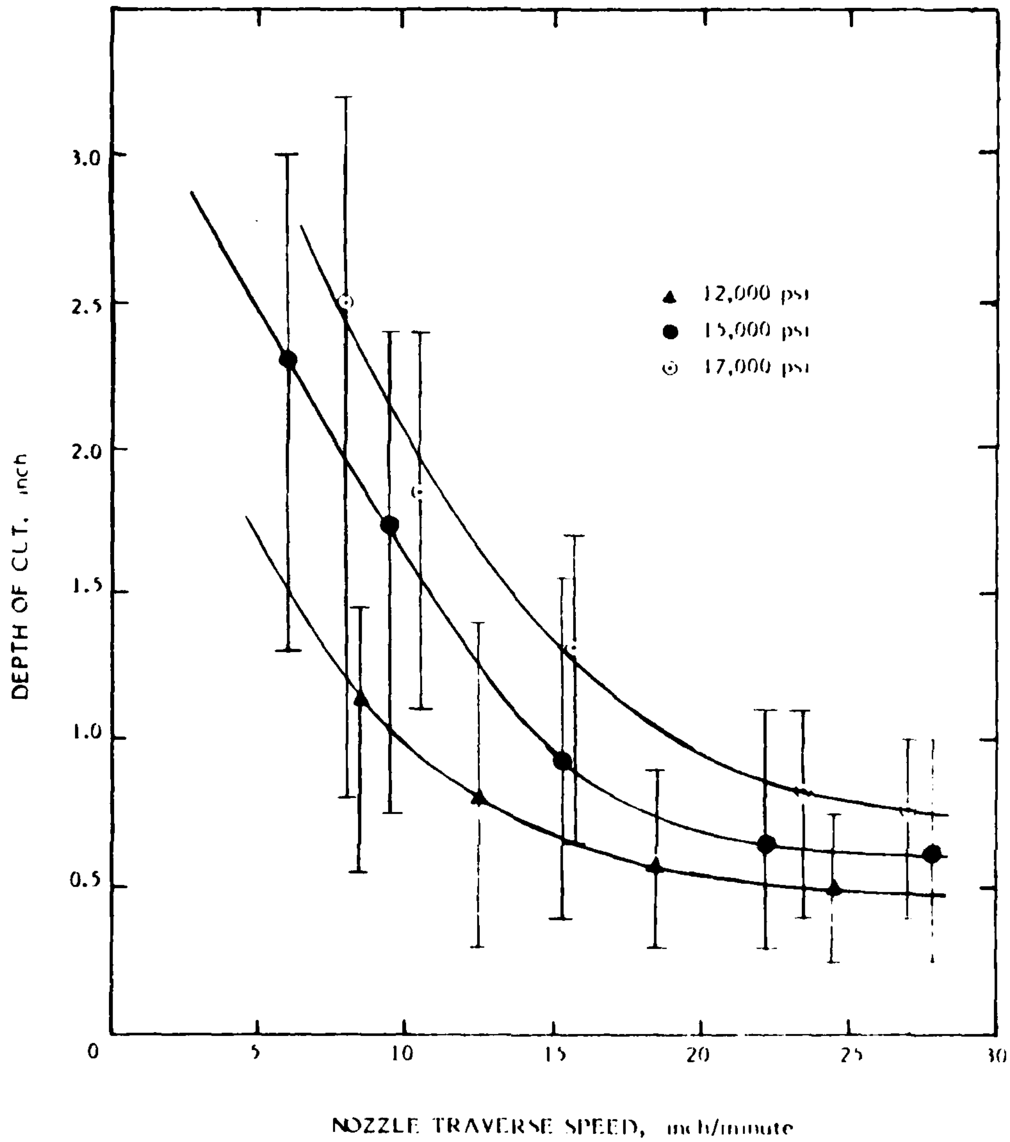
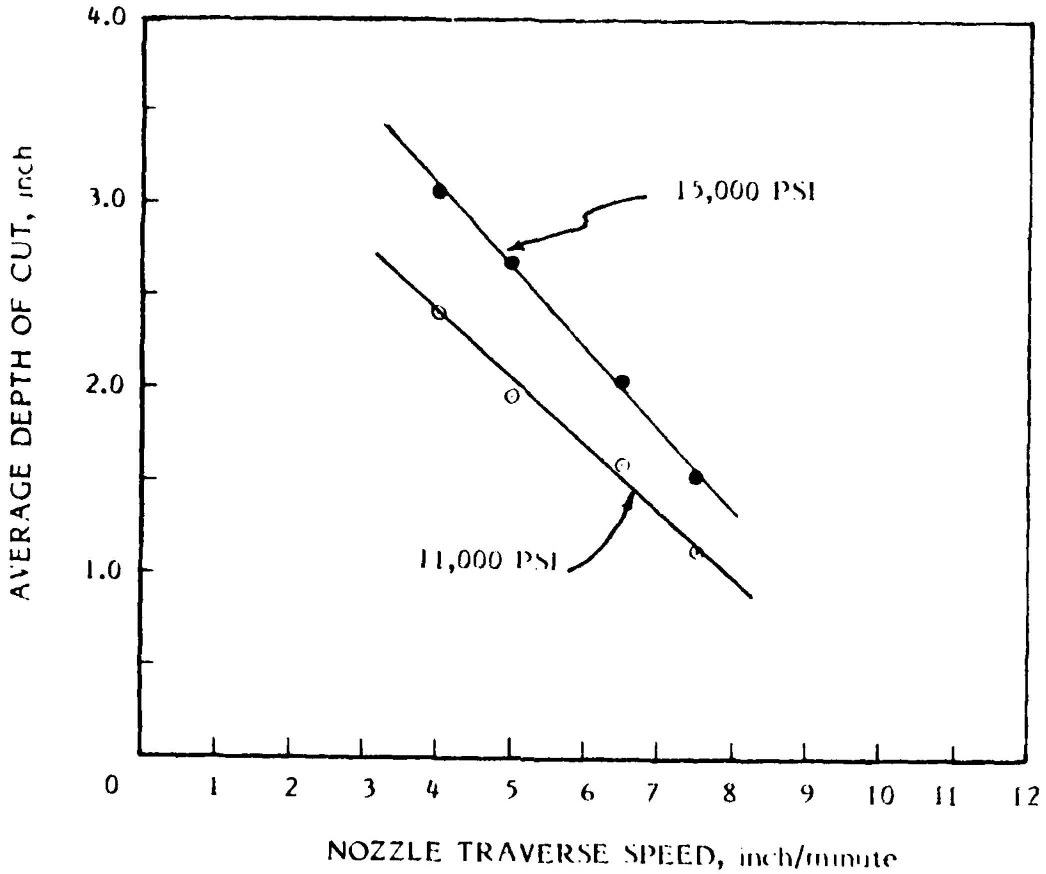


Figure B-10. Effect of Concrete Types on Abrasive Waterjet Cutting.



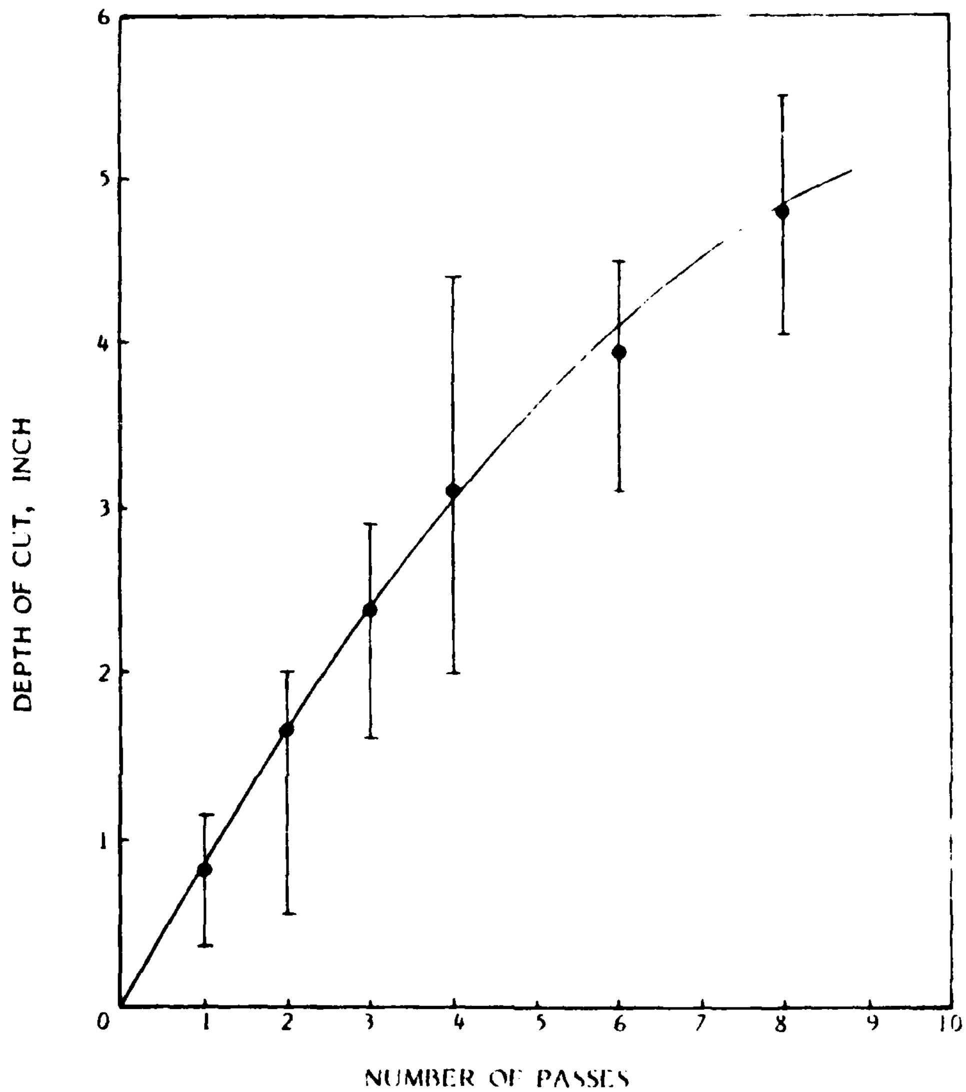
TEST SPECIMEN	Cast Concrete	TEST DATE	12-8-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	26, 23, 22 mils
WATER PRESSURE	Shown above	FLOW RATE	6.2 @ 12,000 PSI 5.8 @ 15,000 GPM 5.5 @ 17,000
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	2 - 3 LBS/MIN.
TRAVERSE SPEED		NOZZLE STANDOFF	0.25 INCH
JET ANGLE	90°	NO. OF PASSES	1

Figure B-11. Depth of Cut vs. Traverse Speed For Different Pressures.



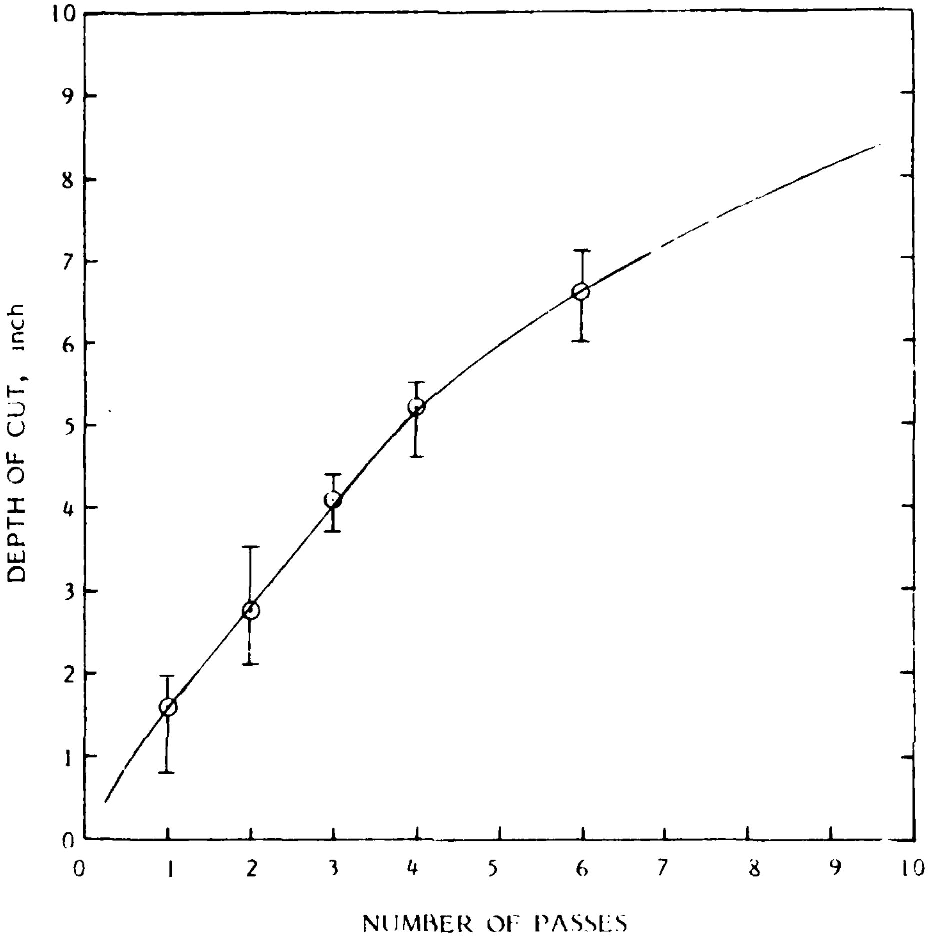
TEST SPECIMEN	Cast Concrete	TEST DATE	12-17-82
ORIFICE CONE	6-Parallel-Jet	ORIFICE SIZE	21 mils, 25 mils
WATER PRESSURE	15,000 & 11,000 PSI	FLOW RATE	6.0 & 6.8 GPM
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	1.8 LBS/MIN.
TRAVERSE SPEED		NOZZLE STANDOFF	0.25 INCH
JET ANGLE	90°	NO. OF PASSES	1

Figure B-12. Depth of Cut vs. Traverse Speed.



TEST SPECIMEN	Cast Concrete	TEST DATE	9-15-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	23 mils
WATER PRESSURE	15,000 PSI	FLOW RATE	5.5 - 6.0 GPM
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	1.8 LBS/MIN.
TRAVERSE SPEED	2.0 feet/min.	NOZZLE STANDOFF	0.5 INCH
JET ANGLE	90°	NO. OF PASSES	

Figure B-13. Depth of Cut vs. Number of Passes (Steilacoom Aggregate).



TEST SPECIMEN	Columbus Concrete	TEST DATE	12-27-82
ORIFICE CONE	5-Parallel-Jet	ORIFICE SIZE	23 mils
WATER PRESSURE	15,000 PSI	FLOW RATE	6.0 GPM
ABRASIVE TYPE	Garnet Grit #36	FEED RATE	2 - 3 LBS/MIN.
TRAVERSE SPEED	2.0 feet/min.	NOZZLE STANDOFF	0.25 INCH
JET ANGLE	90 °	NO. OF PASSES	

Figure B-14. Depth of Cut vs. Number of Passes (Granite Aggregate).

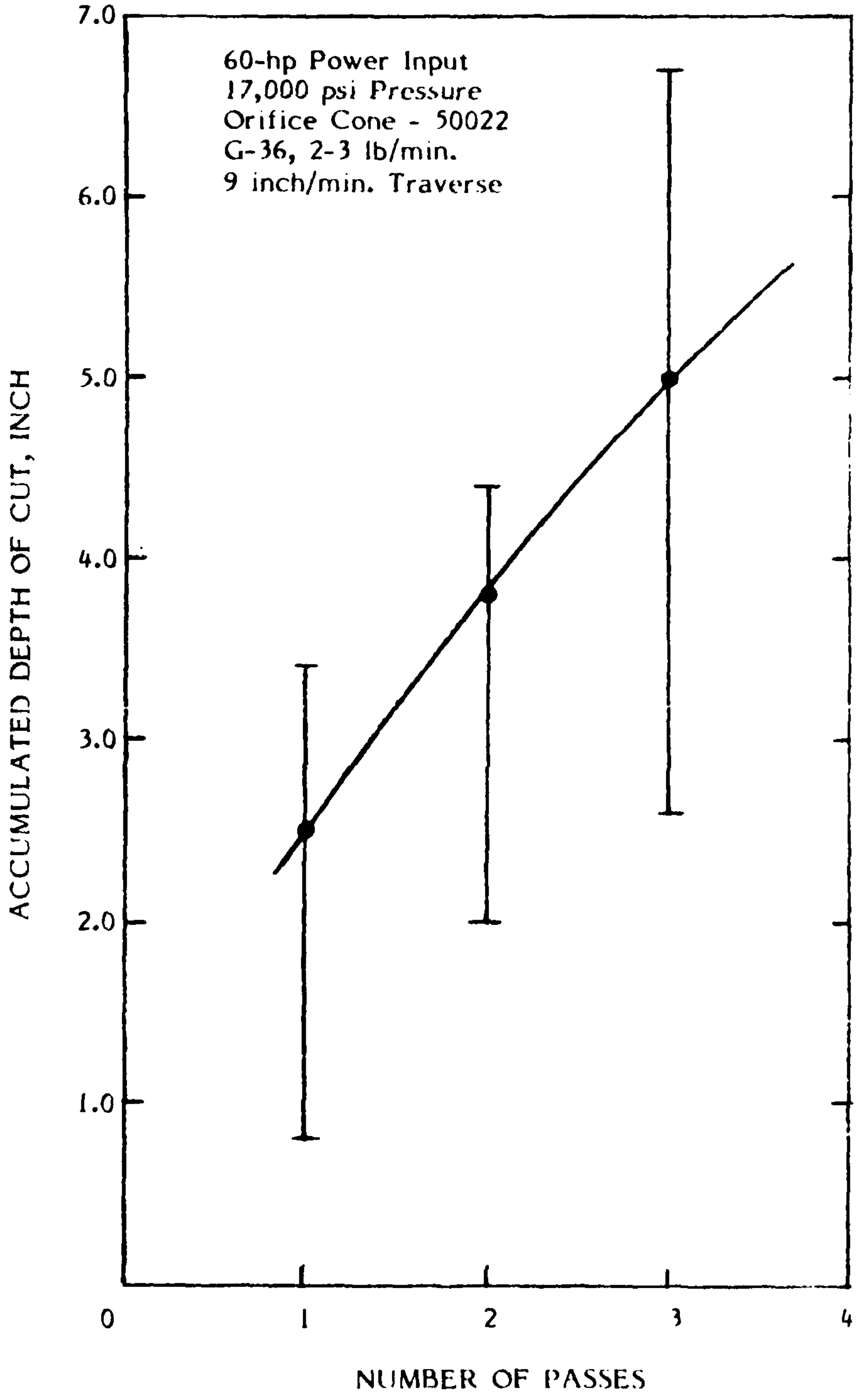
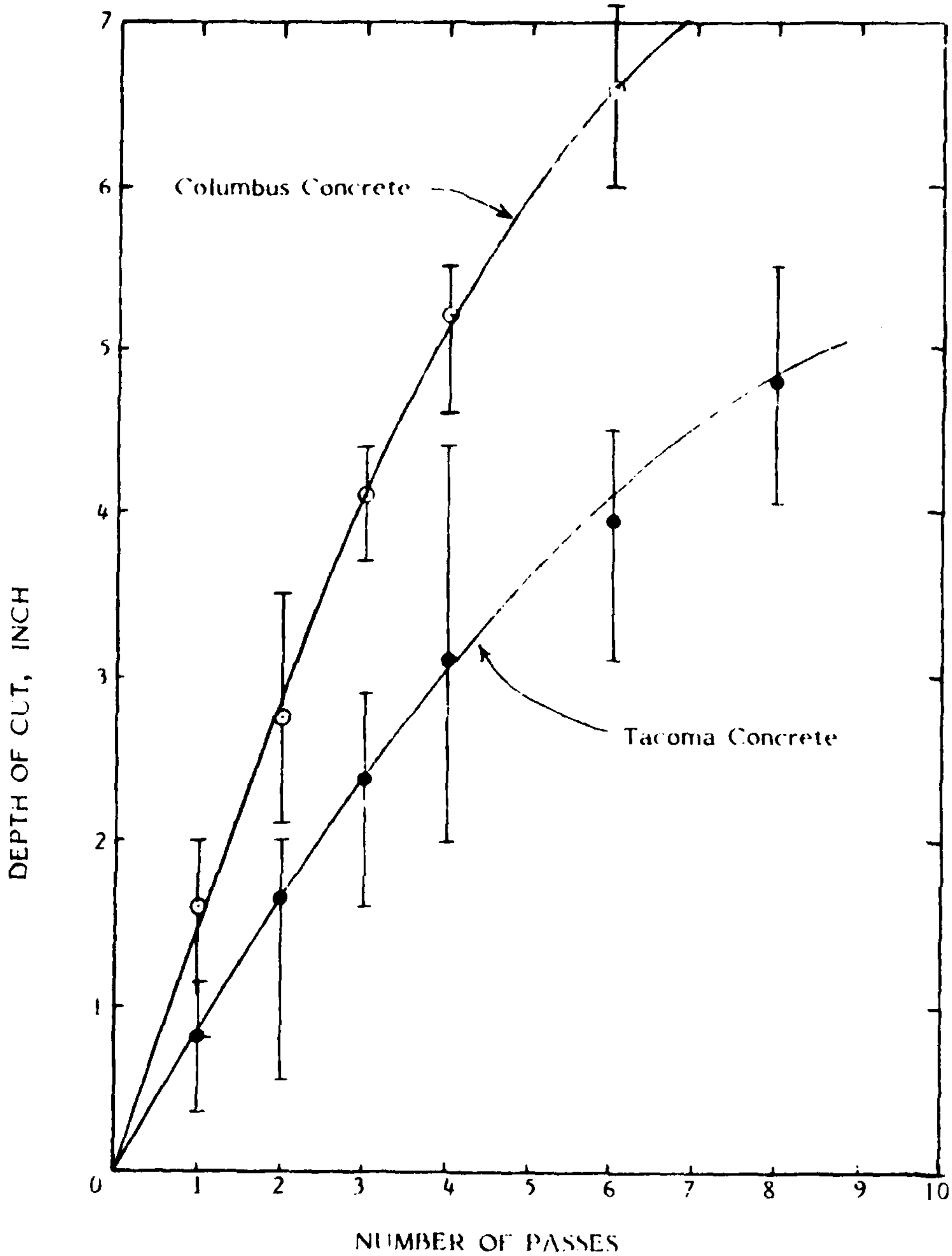


Figure B-15. Depth of 3-Pass Cut at 17,000 psi Water Pressure.



TEST SPECIMEN Columbus, Ohio Concrete / Tacoma, WA Concrete
TEST DATE 12-27-82

ORIFICE CONE 5-Parallel-Jet
ORIFICE SIZE 23 mils

WATER PRESSURE 15,000 PSI
FLOW RATE 6.0 GPM

ABRASIVE TYPE Garnet Grit #36
FEED RATE 2 - 3 LBS/MIN.

TRAVERSE SPEED 2.0 feet/min.
NOZZLE STANDOFF 0.25-0.5 INCH

JET ANGLE 90°
NO. OF PASSES

Figure B-16. Effect of Concrete Type on Cutting Performance.

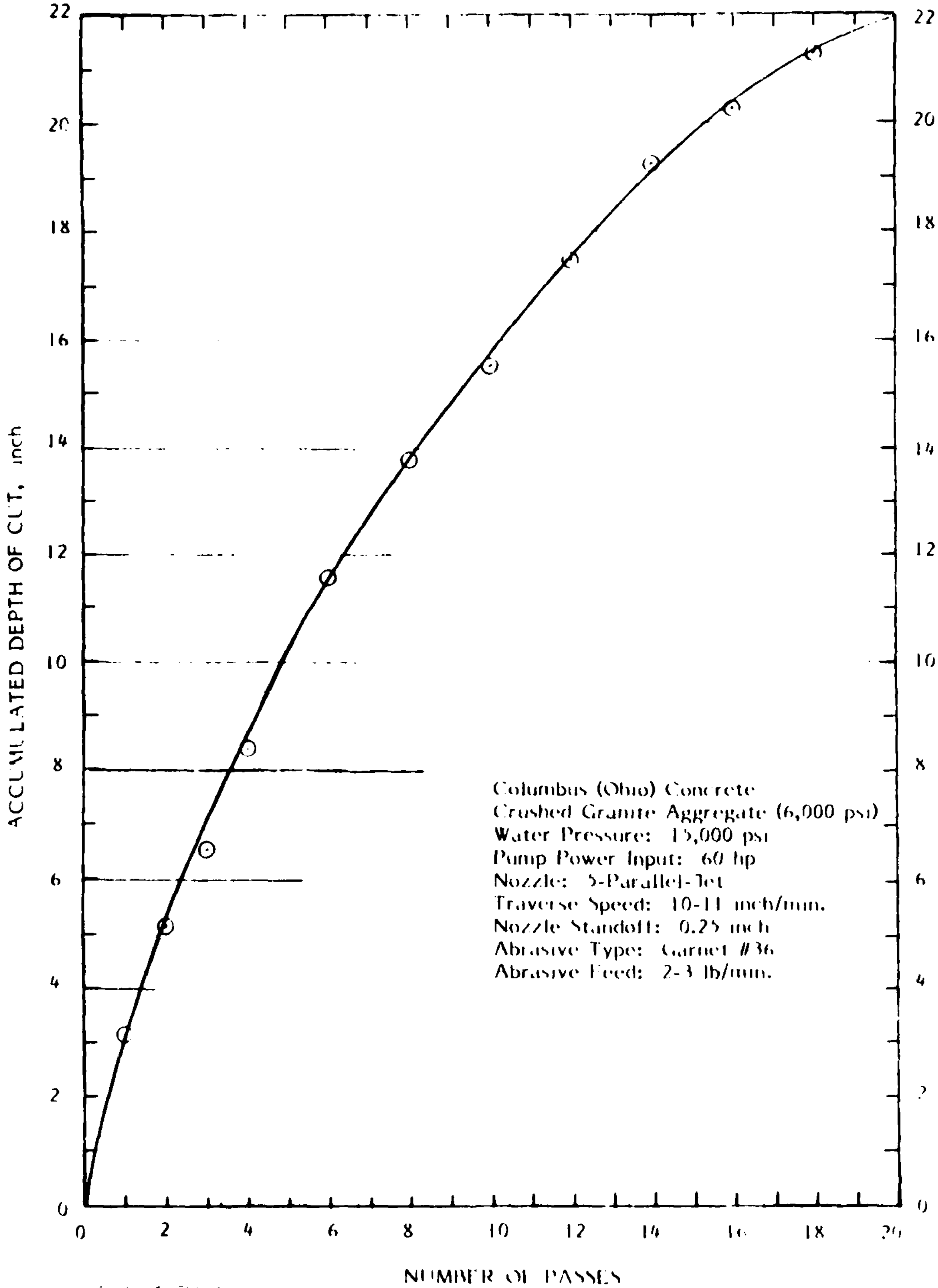


Figure B-17. Accumulated Depth of Cut vs. Number of Passes in Concrete With Granite Aggregate.

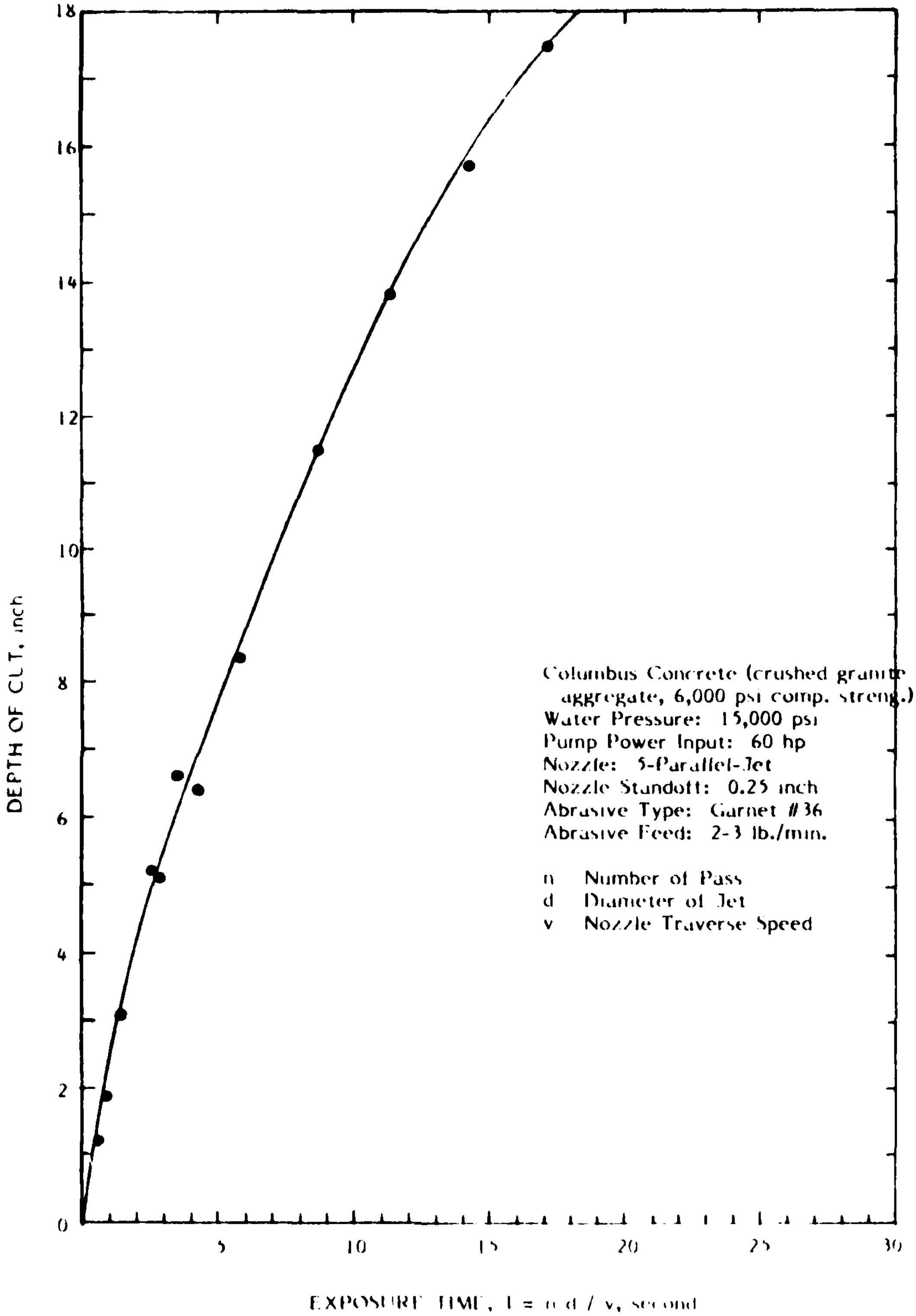


Figure B-18. Depth of Cut vs. Exposure Time.

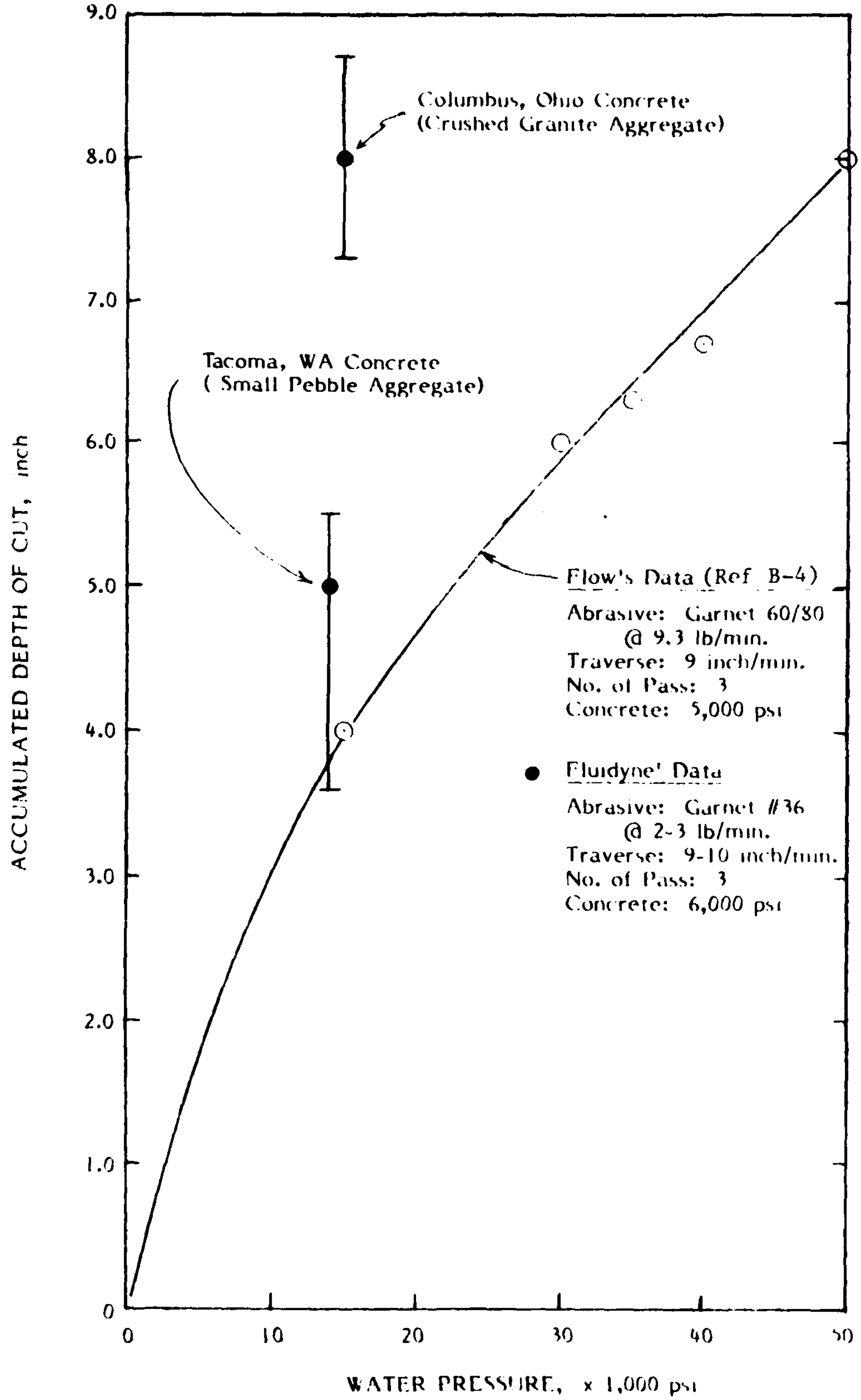


Figure B-19. Comparison of Test Results to Data From Reference B-4.

hard Tacoma concrete as the extra speed of the abrasive particles can have significant benefit in cutting the hard aggregates. With softer concrete, this may not be the case,as a water pressure of 15,000 psi can cut through the aggregates within a reasonable exposure time.

It is projected that an increase in waterjet pressure to 20,000 psi would have a greater impact on cut depth at higher nozzle traverse speed than at slow nozzle traverse speed (Figure B-20). However, at very high nozzle traverse speed, a 20,000 psi abrasive waterjet can only be expected to cut hard concrete to a depth of less than 1 inch per pass (Figure B-21). Thus, several nozzles must be used simultaneously and arranged linearly to produce a cut of greater depth. Such arrangement would require very high power input but otherwise will not encounter technical obstacles.

4. PROTOTYPE SYSTEM DESIGN

a. Key System Parameters

(1) Aggregate in Concrete. In the course of this project, only three different kinds of concrete specimens were tested with the abrasive waterjet, two with pebble aggregates and one with crushed granite aggregate. However, Fluidyne tested the abrasive waterjet with selected rock specimens that included some very hard rock such as rhyolit basalt, quartzite, granite, and hard sandstone. The test results showed that the speed and depth of abrasive waterjet cutting are closely related to the hardness and granular structure (and/or permeability) of rock; the exact relationship is, however, not known to date. Thus, it is reasonable to expect that the hardness of aggregates in concrete would have very strong influence over the cutting capability of abrasive waterjet. Even the best cement is believed to be similar to some soft and medium hard sandstones and can be readily cut with abrasive waterjet. The speed and depth of abrasive waterjet cutting of concrete would vary widely on concrete slabs that contain different types of aggregates. The extent and range of performance deviations, however, remain to be determined. It is reasonable to expect that polished basalt pebbles could be the toughest aggregate for abrasive waterjet to cut because of their extremely dense structure.

(2) Abrasive Type and Feed Rate. For a given concrete, the most important system parameter of abrasive waterjet cutting is believed to be the type of abrasives involved and its mass flow rate. This parameter is of particular importance when hard aggregates are involved. The selected abrasives must be hard, sharp, and capable of withstanding impact of best results. On the other hand, there is the possibility of "overkill" in cutting soft materials with very hard abrasives without getting proportional benefits. This situation is believed to exist in concrete cutting, and the relative hardness and other physical characteristics between the aggregates and selected abrasives are the key factors. From this viewpoint garnet is an excellent abrasive as it is harder than most minerals and can be found in a crystalline structure of good sharpness. Its ability to withstanding impact, however, remains to be studied as large-grain garnets are

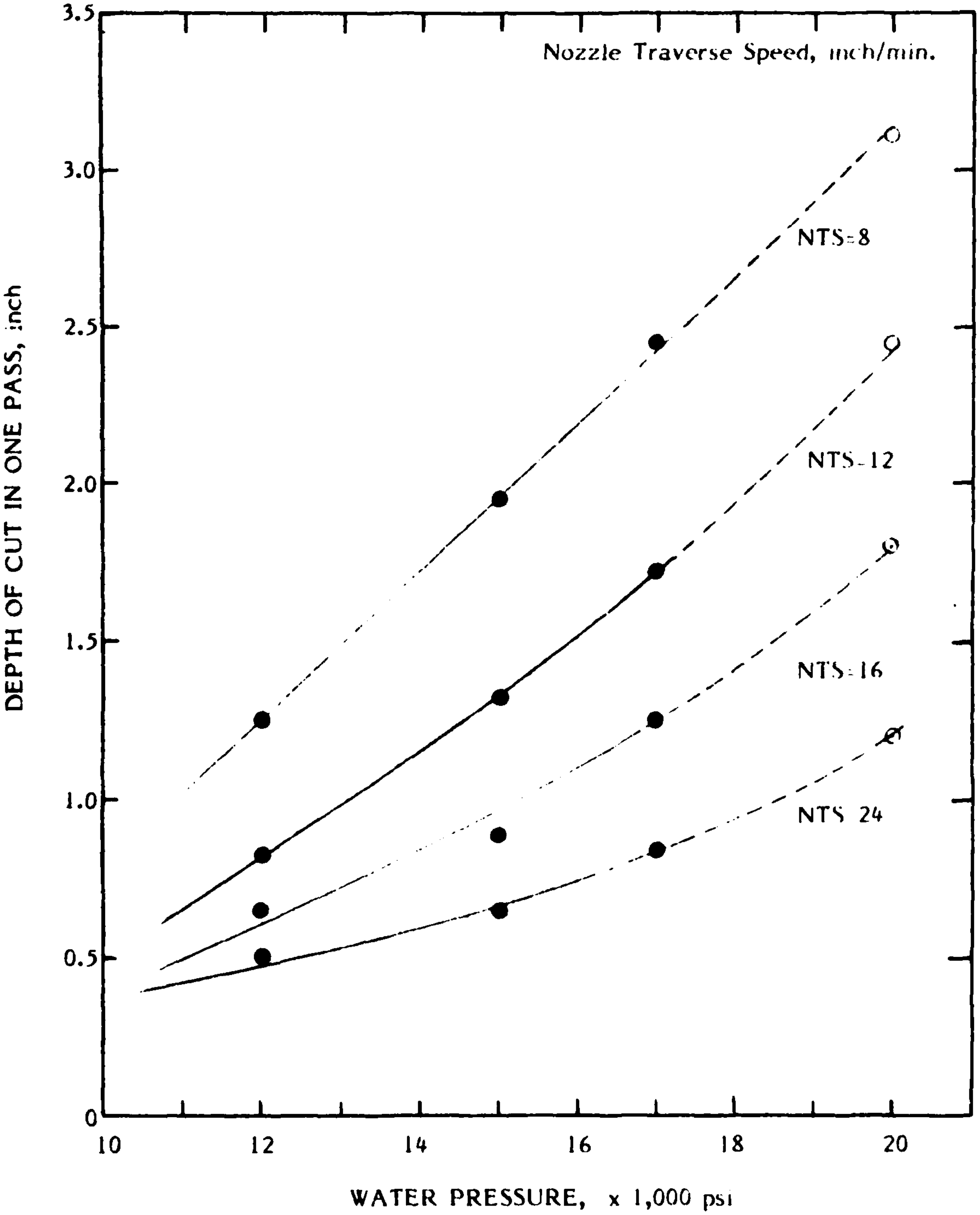


Figure B-20. Extrapolated Depth of Cut at 20,000 psi Water Pressure.

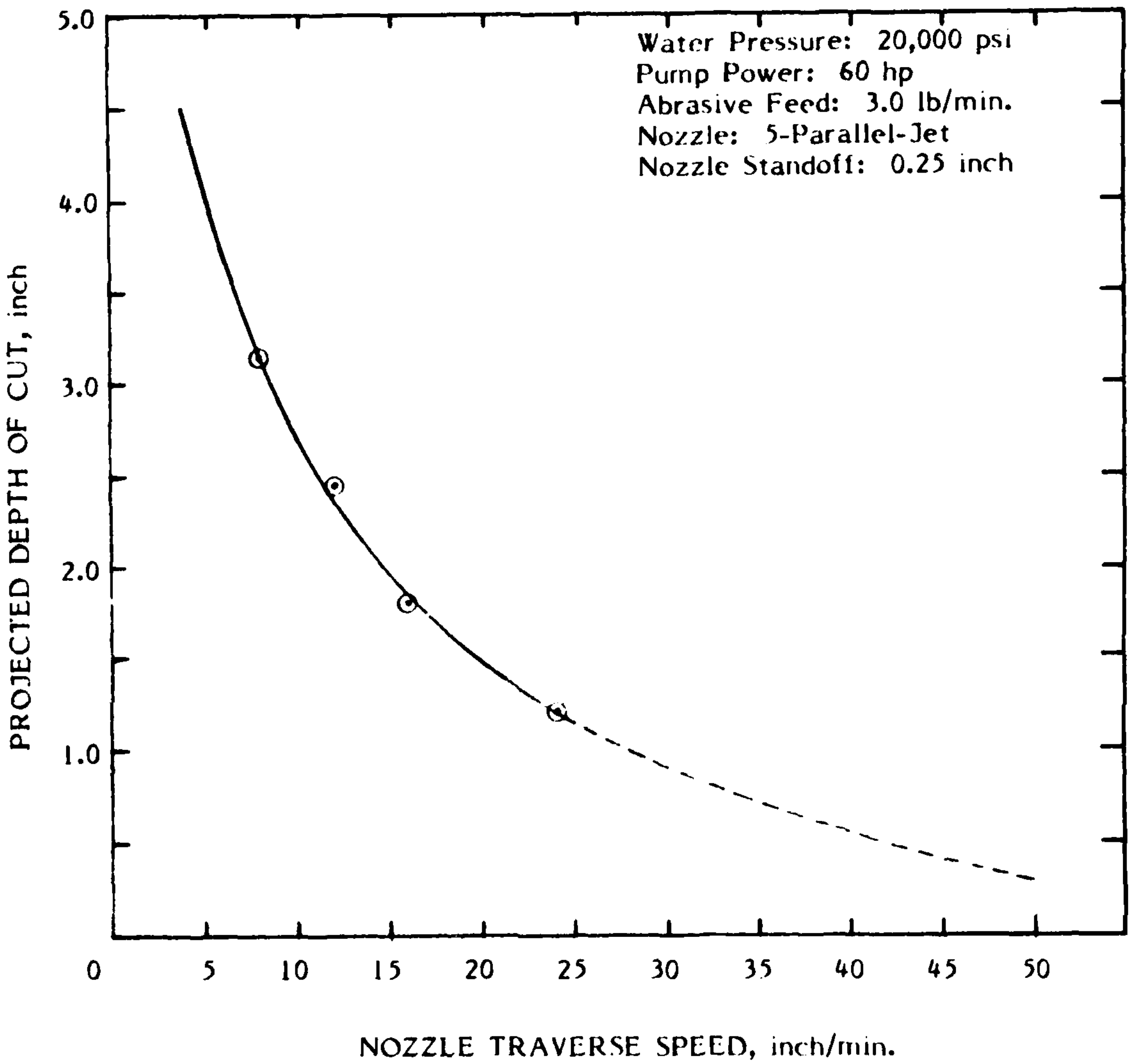


Figure B-21. Projected Depth of Cut at 20,000 psi Water Pressure.

known to have faults and fractures. Glacial sand is probably the second best choice as it often contains very sharp grains. There are also other types of natural and manmade abrasives; their effectiveness in abrasive waterjets remains to be studied.

For a given concrete and selected abrasives, the abrasive waterjet's cutting capability is proportional to the amount of abrasives entrained in the jet. It should be observed that the amount of abrasives consumed is a different matter, a large quantity of abrasives can be thrown through a waterjet nozzle without producing much benefit if the amount entrained into the waterjet is small. With Fluidyne's nozzles, the amount of abrasives that can be entrained is quite high and is found to vary with several factors, including jet configuration, water flow rate, water pressure, and nozzle design. Latest tests have shown that up to 6 pounds/minute of large-grain granite can be introduced into current nozzles to produce good cutting. Further, the depth of cutting increases with the increase in abrasive feed rate until the abrasive flow was choked; the exact cause of choking of abrasive flow is not clearly known at present. Tests at a constant pump horsepower have shown that deeper cuts can be produced by lowering water pressure and increasing water flow rate because a greater amount of abrasives are allowed to be entrained into the waterjets. Such observation indicates that the amount of water affects the quantity of abrasives entrained, and thus the amount of abrasives consumed. On the other hand, using a larger flow-shaping cone can also increase the abrasive feed rate without producing noticeable benefit in cutting. Change in jet configuration can certainly affect the abrasive entrainment and consumption as well. Thus, the relationship between abrasive flow rate and abrasive waterjet cutting is complex and deserves additional investigation; improved techniques to differentiate the abrasive consumption and entrainment would be of significant value. Fortunately, the nozzles used in this program have a high capability to entrain abrasives such that the amount of abrasive introduced is not as sensitive a subject as it would otherwise be.

In limited testing, dry abrasives have been found to be much more effective in cutting concrete than abrasives in the form of a slurry. This effect has been anticipated to some degree. The preparation of a water-based slurry requires a fine abrasive. Larger size abrasives, which can be more productive in cutting, are not efficiently suspended in the slurry. The presence of the water in the slurry itself can perturb the coherence of the jets as the abrasive is introduced. Thus, the use of abrasive slurry is not expected to produce any benefit in RRR applications where the speed of cutting is of primary concern.

The use of dry abrasives requires a good metering and feed system; such a system is not currently available from commercial sandblasting equipment suppliers. Ideally, this system should be self-regulated by the vacuum generated at the abrasive waterjet nozzle to obtain maximum feed rate without blockage and to achieve maximum cutting rate. On the other hand, the flexibility in adjusting the abrasive flow rate to meet different cutting needs is also a desirable feature.

(3) Water Pressure. The factor of water pressure is placed third because its exact effect on abrasive waterjet cutting of concrete is not clearly known. In the course of this project, the water pressure was varied from a few thousand psi to a maximum of 17,000 psi. The benefit of increased water pressure was clearly observed with Tacoma concrete but not with Columbus concrete if other factors are not changed. The test results of this project and that of published literature also showed that the capability of abrasive waterjet can be greater at lower water pressure if a more efficient nozzle is used.

However, with all factors considered there is no doubt that the capability of abrasive waterjet can be improved by increasing the water pressure when other factors are held constant. The improvement should be particularly noticeable in cutting hard aggregates and in making deep cuts. This is simply due to the increase in the velocity of abrasive particles, which is believed to be closely related to the velocity of waterjets that, in turn, is proportional to the square root of water pressure.

Another factor should be examined. This is the relationship between the water pressure and jet dispersion in which the dispersion of waterjet is enhanced by increase in water pressure. The jet dispersion, in turn, may affect abrasive entrainment in a given nozzle and must be considered in nozzle design. It is possible, however, to design an abrasive waterjet nozzle that can be readily adjusted to suit the water pressure involved without sacrificing abrasive entrainment.

When the system power and cutting efficiency are not considered, it is reasonable to conclude that high water pressure should be employed for high-speed cutting of concrete. A pressure level greater than 40,000psi would be preferred and high-power pressure intensifiers could be used to generate such pressure levels. Fluidyne's basic nozzle design can accommodate such pressure levels without any major modifications.

(4) System Power. The relationship between the pump power and abrasive waterjet cutting of concrete has not been resolved in this project. The power input to a waterjet pump system can be reflected by the water pressure and flow rate. Thus, a given power input can be used to generate high-pressure-low-flow or low-pressure-high-flow systems, or others in between. The flow rate of a waterjet system is known to affect the entrainment of abrasives, thus affecting the concrete-cutting rate of abrasive waterjet. At this point, it is not clear how the abrasive waterjet's cutting capability is balanced between pressure and water flow rate because of the complex interactions of abrasive entrainment and concrete types. There is no doubt, however, that increased pump power will increase the abrasive waterjet's cutting capability and high-speed cutting of concrete will require enormous power.

In view of the speed requirement of the RRR program, it is necessary to examine how the speed of concrete cutting can be increased without increasing the pump power to exhorbitant levels. One possibility,

of course, is to slot the concrete without shearing all aggregates. Abrasive waterjets can be used to cut the cement rapidly while skipping some of the larger aggregates. As a result, a wide groove is made, with many of the aggregates being washed away from the cut surface. This approach could be particularly feasible in cutting concrete that contains small, hard pebbles while not too feasible with large, crushed aggregates. In applying this approach, a low-pressure-high-flow system would be more appropriate than a high-pressure-low-flow pump system. For example, the Tacoma concrete can be cut with a 10,000 psi abrasive waterjet system by removing the cement between the aggregates; the cut edge, however, is very ragged.

The test results available to date have also shown that the cutting of concrete with abrasive waterjet is much faster than that of using straight waterjet. As far as the RRR program is concerned, the edge quality is probably the only question that needs resolution. Thus, this fast slotting of concrete without severing all aggregates deserves attention and study.

b. Prototype Nozzle Systems

(1) Vertical or Inclined Nozzle System. Available test data have shown that the depth of cut in concrete is proportional to the amount of the abrasive waterjet dwell time on the concrete. Thus, any attempt to increase the cutting speed must include optimizing the jet dwelling time. One way to accomplish this purpose is to direct the abrasive waterjets in parallel with the concrete slab, as shown in Figure B-22. This approach involves first making a cut through the concrete with the nozzle assembly in a horizontal position and then straightening the nozzle assembly to a vertical or inclined position prior to advancing the nozzle assembly.

With this approach, the dwelling time is probably the longest among all other possible approaches. It is feasible to open a wide groove in concrete if there are no steel reinforcing rods and the pump system can deliver sufficient water flow. For cutting 12-inch thick concrete, a total of less than 12 nozzles would do the job, each being responsible for about 1-inch square of the frontal surface. Such closed spaced nozzles could generate vigorous jet interactions to maximize abrasive turbulance and concrete removal. The abrasive waterjet nozzles can be positioned in an angular pattern to assure wide cut, as shown in Figure B-23. The required pump for this approach can be minimized if the system is designed not to cut through all aggregates. Therefore, it may not be feasible if the aggregates are large as a very wide groove (wider than the width of nozzle manifold plus the diameter of the largest aggregates) must be made to allow the advancement of nozzle assembly, as shown in Figure B-24. Nevertheless, this approach must be adapted if the speed of cutting is of primary concern. It is unlikely that a water pressure much higher than 10,000 psi is necessary for implementing this approach; the flow rate, on the other hand, could be as high as 100 gpm. The abrasive consumption could be maintained at a reasonable level as only cement is being removed.

(2) Horizontal Nozzle System. If the speed of cutting is not critical and higher quality of cut edge is desired, a different nozzle system arrangement will be required. In such a case, a bank of abrasive waterjet nozzles arranged in a line pattern could be used, as shown in Figure B-25. With this approach, each nozzle is assigned to cut a groove of certain depth and the total number of nozzles is governed by the total depth and cutting speed involved. The nozzle assembly is arranged to stay on the concrete surface so that the abrasive waterjets can cut the full depth without penetrating into the groove. The nozzles can also be designed and positioned to achieve special purposes. For example, the first few nozzles can be assigned to cut a groove of given width while the last few nozzles can be assigned to obtain maximum depth. Further, the nozzles can be positioned to obtain maximum benefit in jet dwelling time, interactions and abrasive turbulence without jet interference. The maximum cutting speed attainable is basically governed by the available pump power. Meeting the RRR's target speed of 30 feet per minute, however, would require an enormously high level of power input; a minimum of 1,000 horsepower is believed to be required. Further, high water pressure may be required for such high-speed cutting because the delivery of abrasives must be at high speed as well.

(3) Synergistic Approaches. There are possible synergistic approaches of combining abrasive waterjet with other technologies to achieve high-speed cutting of concrete. However, specific approaches that may increase the cutting speed to RRR's target level are difficult to conceive at present as the speed of abrasive waterjet cutting is lagging behind. One possible approach is the combination of a mechanical pick and narrow slotting with abrasive waterjet. In this approach, abrasive waterjet is used to make a parallel cut, while a mechanical rock pick is used to remove the strip of concrete between the two cuts. Thus, it is basically similar to the waterjet-assisted rock cutting with a pick except that straight waterjet is replaced with abrasive waterjet. Since the abrasive waterjet cuts to be made are quite narrow, the power output of each nozzle can be quite low and the total pump power can be significantly reduced as compared to a pure abrasive waterjet system. On the other hand, the total system power may still be quite high as the picks must exert sufficient force to break the concrete strips. The converging jet abrasive nozzles could be particularly useful in this approach. It is estimated that the required pump power could be reduced by a minimum of 50 percent, while the abrasive consumption could be reduced by up to 75 percent, depending upon the nozzles involved.

With this abrasive jet-mechanical pick approach, a wide cut can be made without consuming enormous amounts of power. Thus, the nozzle assembly can be lowered into the cut to gain great depth.

REFERENCES

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B-2. Barton, R. E. P. and Saunders, D. H., "Water/Abrasive Jet Cutting of Concrete and Reinforced Concrete," Paper K4, 6th ISJCT, Surrey, U. K., April 1982.

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B-4. Hashish, M., "The Application of Abrasive Jets to Concrete Cutting," Paper K2, 6th ISJCT, Surrey, U. K., April 1982.

B-5. Hashish, M., "Steel Cutting With Abrasive Waterjets," Paper K3, 6th ISJCT, Surrey, U. K., April 1982.

APPENDIX C

WATERJET-ASSISTED MECHANICAL CONCRETE CUTTING

APPENDIX C

WATERJET-ASSISTED MECHANICAL CONCRETE CUTTING

The material in this appendix was prepared by Engineering and Science Technology, Inc., 108 S. Eldridge Way, Golden, Colorado 80401 under subcontract to The BDM Corporation between March 1982 and January 1983. The tests were conducted at the Earth Mechanics Institute of the Colorado School of Mines.

1. INTRODUCTION

The technique of concrete cutting or slotting with diamond sawing has been very successfully employed for highway repairs, concrete slab removal in building floors, and other civil works. However, the fundamental process of this method is grinding, thus limiting the rate of cutting. Diamond concrete sawing is reaching its best possible efficiency through improvements made over the past years with little possibility of great advancement in the cutting rate in the near future.

Several advanced methods, now being developed, show good promise. One is the application of a high-pressure waterjet with penetrating or rotational nozzles (Reference C-1) at high water pressure of 30 to 40 ksi range. A fraction of a square foot of rock slotting and 2/10 square foot of concrete cutting per minute have been achieved. The difficulty of the above high-pressure waterjetting method is the inefficient cutting removal process and the high energy consumption when slots reached several inches in depth. The long-term prospect is good for a high rate of slotting but no dramatic breakthrough is anticipated.

The use of an abrasive jet for concrete cutting is a very promising technique (Yie, Gene, Private Communication). It can reach a cutting depth of 10 to 12 inches with a single narrow slot. The best current rate is estimated at a traverse speed of about 12 to 24 inches per minute with a depth of 6 inches, or less than 1 square foot per minute. With further development, this technique has the potential to be a viable method of concrete cutting with good rates.

The most promising technique which may meet the military need for concrete slotting at a rate of closer to 30 ft^2/minute is the waterjet-assisted mechanical rock-cutting method (References C-2 and C-3). The current rate achievable in 20,000 psi sandstone with a single tool is 4 ft^2/minute. It is feasible that with the proper use of multiple-cutting tools, a 30 ft^2/minute slotting rate may be achievable by good mechanical design. The technology of concrete cutting may be established if this rock-cutting technique can be proven to be equally applicable to concrete slotting with a similar rate.

2. BACKGROUND AND REVIEW OF LITERATURE

a. Background

The method of waterjet-assisted mechanical rock cutting has been demonstrated to be very effective for a variety of rocks with compressive strength ranging from 10 to 40 ksi (References C-2, C-3, and C-4). The principle of this technique is that a waterjet directed at the crushed zone which is created by a mechanical tool extends the cracks by hydrofracturing. Hydrofracturing is an efficient method which requires a relatively low water pressure of 5 to 10 ksi which is lower than the pressure for kerfing of rock with waterjets. In the jet-assisted mechanical rock-cutting system, the forces on the mechanical tool are also reduced and bit life increased. Reduction of both thrust and cutting forces may be 50 percent or more with jet-assisted cutting (Reference C-2, Figures C-1 and C-2). From the laboratory result, the cutting rate of 20,000 psi sandstone may reach 4 ft^2/minute or more using a single pointed pick with a water pressure of 5,000 psi (Reference C-3).

This jet-assisted mechanical system may be applied for concrete cutting with high productivity. In addition to the principle described above, this cutting system may have a special effect in concrete slotting, i.e., the high-pressure jet removes the cement and sand matrix to expose the stone and the mechanical tool breaks and removes the stone which is difficult to cut by a waterjet alone. With this possible special effect, this method may achieve a higher rate of cutting concrete than cutting rock of equivalent strength.

b. Individual Publications

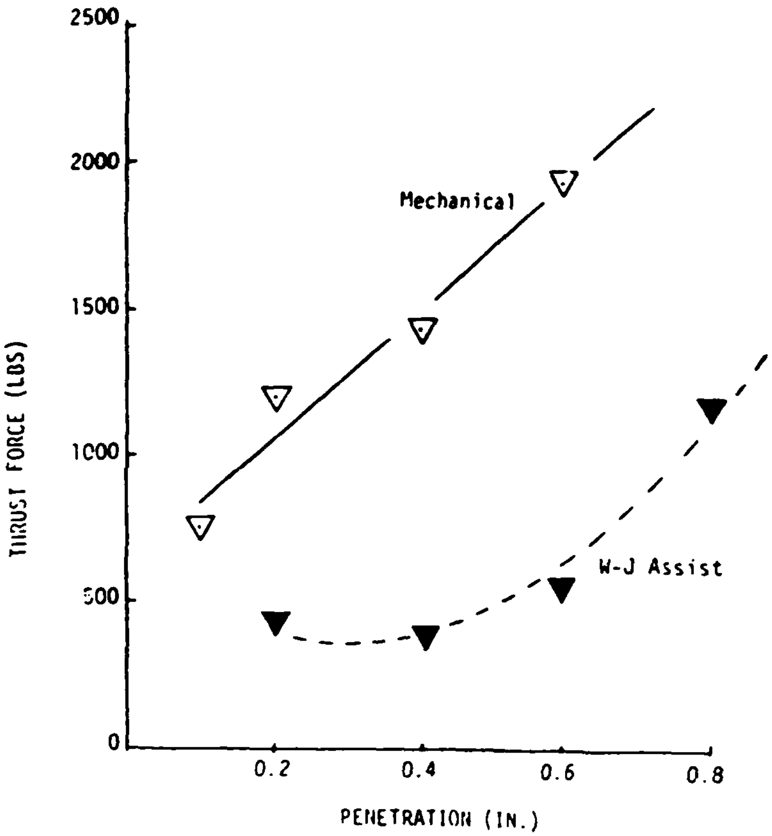
(1) Papers by Wang (Reference C-2), and Ropchan, Wang and Wolgamott (Reference C-3). These are the two publications which contain the most direct information and test data relevant to waterjet-assisted concrete cutting. Several pertinent points are summarized as follows:

(a) A pointed pick has more consistent cutting force wear than radial picks. It is, therefore, a better pick to be used for rock (hard material) cutting.

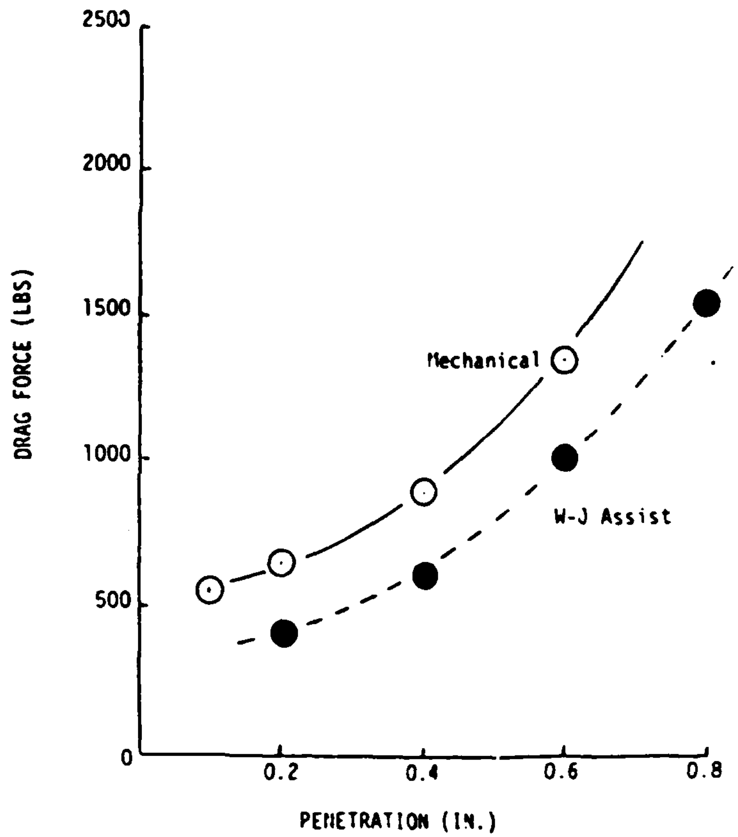
(b) A pick cutter can be used to cut a variety of rock types, with strengths up, to 20,000 psi to 0.7 inch depth per pass. A reduction of normal force by 40 percent and drag force of 30 percent can be attained with a jet pressure of only 5,000 psi.

(c) Only low water pressures of up to 10,000 psi are required to produce the special effect of hydrofracturing.

(d) Jet impinging from behind is more effective than in front of the pick.



Thrust Reduction Due to W-J Assist Wedge Type Drag Bit in Sandstone Independent Cuts



Drag Reduction Due to W-J Assist Wedge Type Drag Bit In Sandstone Independent Cuts

Figure C-1. Force Reduction Resulting From the Use of Waterjet Assistance.

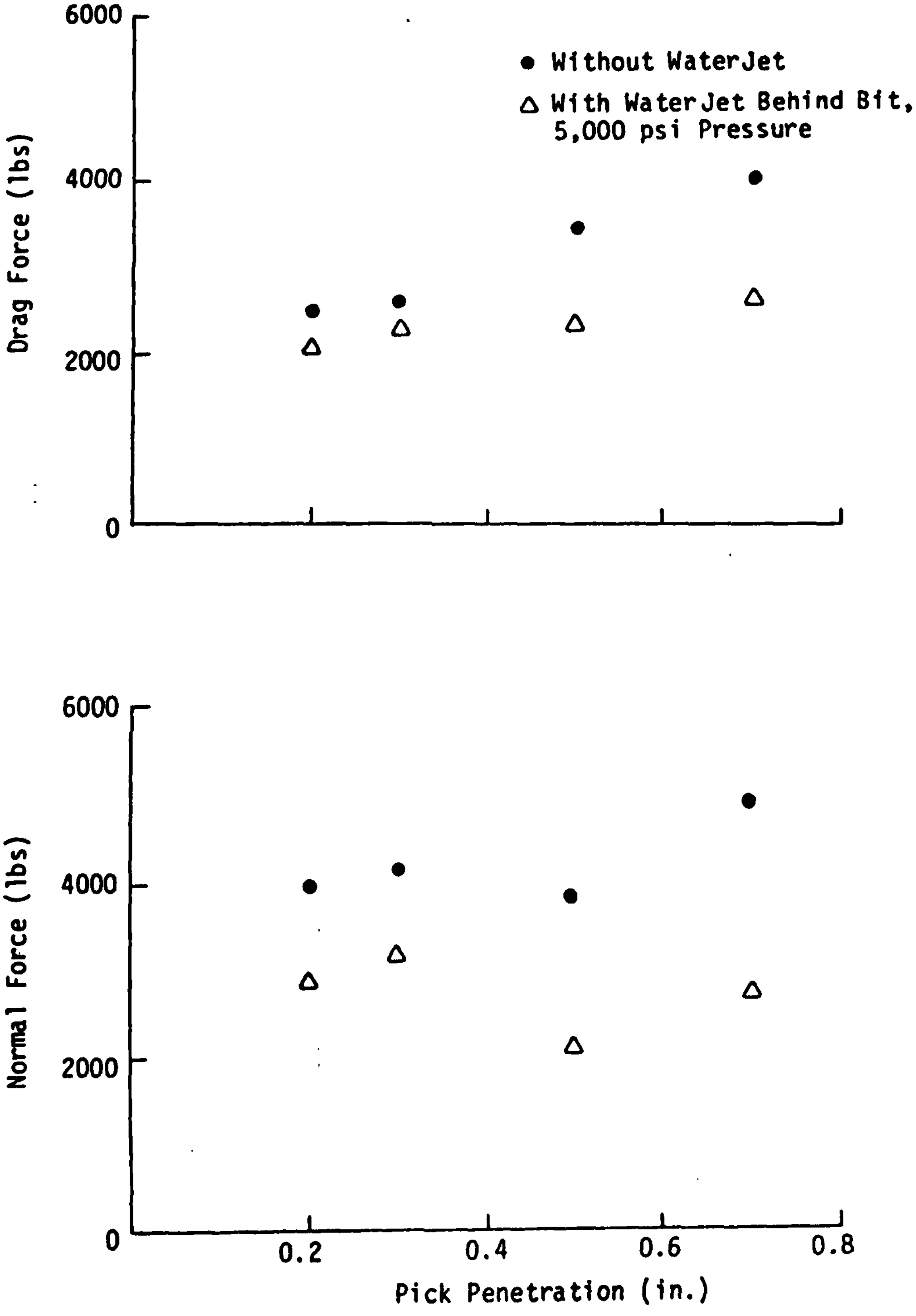


Figure C-2. Variation in Cutting Forces With Bit Penetration For Unassisted and Waterjet-Assisted Cutting Using a Conical Bit in Sandstone, Cut Spacing: 1.5 Inches.

(2) Report by National Coal Board (Reference C-6). This report not only verifies that a waterjet-assisted pick rock cutting works in the laboratory but it also is effective when incorporated in a real machine under field conditions. The machine had a reduction of over 40 percent in thrust force and over 30 percent in cutting force when cutting limestone of 17,000 psi with the assistance of a waterjet at 10,000 psi pressure. The vibration of the machine was reduced and pick life improved.

(3) Paper by L. Bauman (Reference C-7). The type of cutting tool used in this investigation was the drag bit which has a wide cutting edge and employs a slightly different cutting mechanism than a pointed pick. However, the effect of waterjet assistance is also evidenced through the reduction of normal and cutting forces for rock slotting. A slot of about 2 ft^2/minute was produced in hard sandstone of 20,000 psi compressive strength at a water pressure of about 25,000 psi.

(4) Paper by O. Dubugnon (Reference C-5). This paper also confirms that low-pressure waterjets of less than 15,000 psi are effective in assisting rock cutting with drag bits. The force reduction in general is about the same at various depths but in some instances the waterjet is more effective for deeper cuts than shallow cuts.

(5) Paper by M. Hood (Reference C-4). This paper reports the results of cutting hard quartzite in South Africa by using a drag bit. Hood found by aiming two jets into the high stress zone near the corners of the drag bit, twice the depth of dry cut could be obtained with the same driving force at water pressure of 5,000 psi.

(6) Paper by I. A. Kuzmich (Reference C-8). Experimental results and analytical relationships of hydromechanical breakage of rock and coal using a disc cutter in the laboratory were presented. Although the information is not pertinent to pick cutting, the correlation of pressure, depth of cut and mechanical forces is beneficial to concrete cutting.

c. Mechanism of Waterjet-Assisted Mechanical Rock Cutting

As suggested by Wang (Reference C-2) and Dubugnon (Reference C-5), the mechanism of waterjet-assisted mechanical rock cutting is that the high-pressure water assists to extend or hydrofracture the microcracks formed underneath the mechanical pick. Therefore, the pressure required is much smaller than waterjet kerfing of the rock. As discussed in the literature (References C-2 and C-5), a pressure up to 15,000 or 20,000 psi is sufficient to create significant reductions in thrust and cutting forces on a mechanical pick.

This mechanism may be depicted as shown in Figures C-3 and C-4. The jet is more effective from behind, as shown in Figure C-4, because it is in line with and goes directly into most of the cracks. However, it is difficult to place the jet from behind due to geometrical constraints on cutting structures.

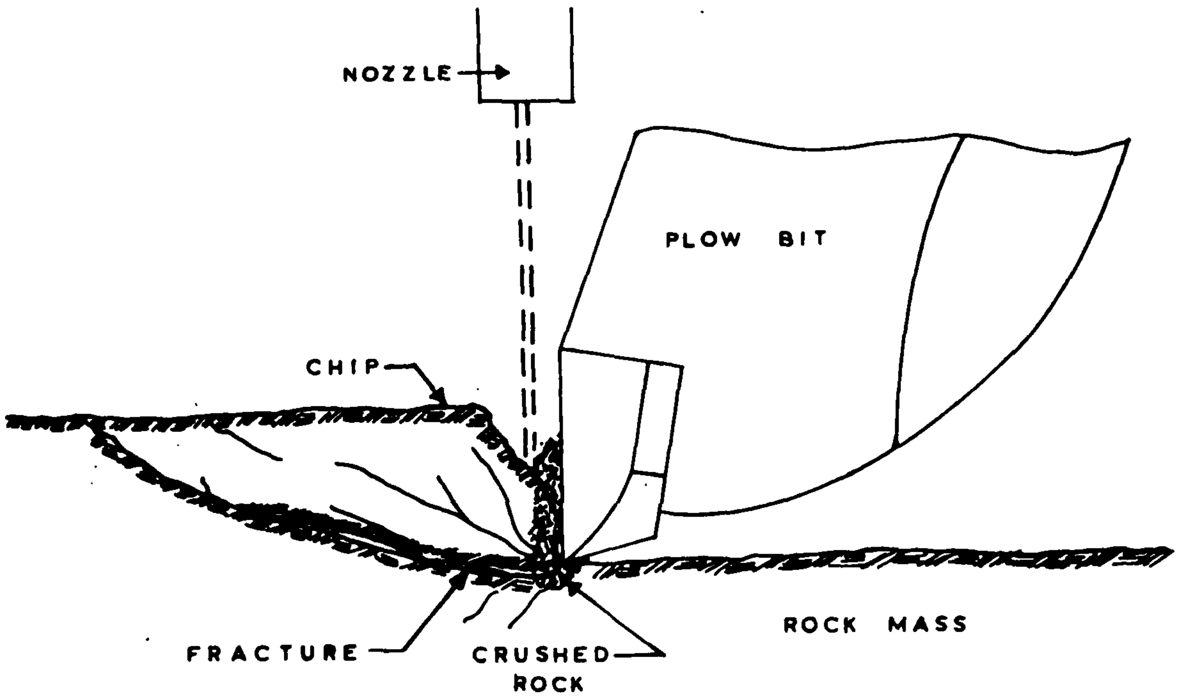


Figure C-3. Rock Fracturing Due to Plow Bit - Waterjet in Front of Bit.

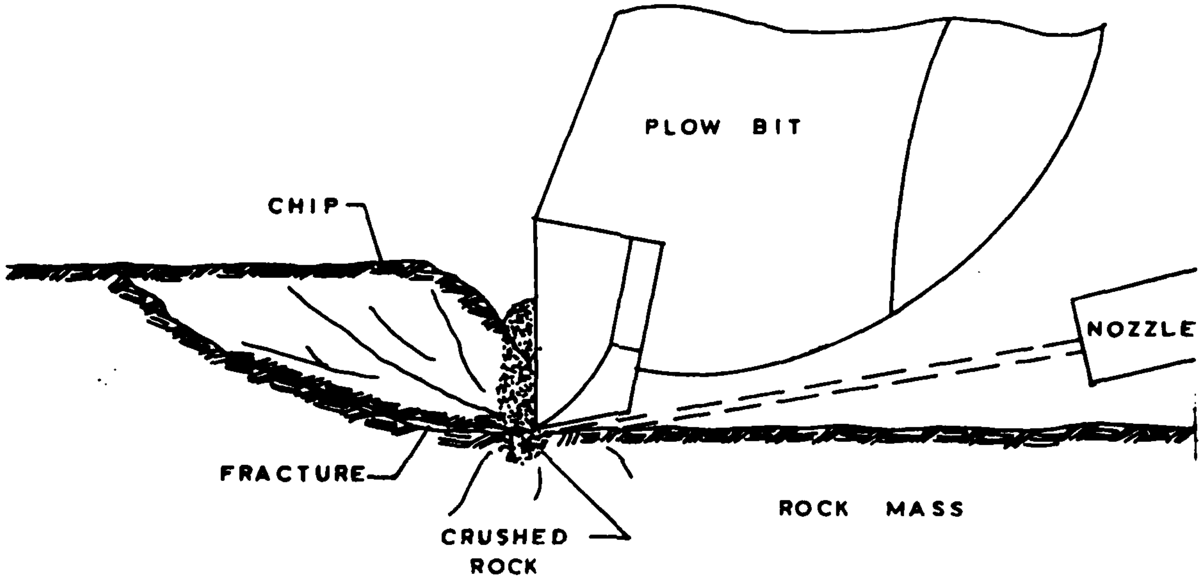


Figure C-4. Rock Fracturing Due to Plow Bit - Waterjet Behind Bit.

d. Data Analysis

The Dakota sandstone has the same compressive strength (6,000 psi) as the concrete tested. Therefore, the data on Dakota sandstone by Ropchan, et al. (Reference C-3) were analyzed. As shown in Figures C-5 and C-6, the normal and drag forces versus jet pressure at various penetrations are plotted. The normal forces at 1/2 and 3/4 inch penetration are estimated as 800 and 1,000 pounds, respectively, at 10,000 psi jet pressure. The drag or cutting forces at 1/2 and 3/4 inch penetration are estimated as 1,800 and 2,700 pounds at a jet pressure of 10,000 psi. Certainly, the assumption of concrete cutting with the same depths of cut as in Dakota sandstone produces the similar forces in a reasonable approach. However, it is recognized that Dakota sandstone has a higher porosity and the tensile strengths of both materials are not known. Because of these unknowns, rock cutting data and behavior can only be considered an approximation of what can be expected for concrete cutting.

3. LABORATORY TESTING

a. Objectives

The objectives of the laboratory experiments are to obtain: (1) basic waterjet kerfing data, (2) a mechanical pick concrete-cutting data base, and (3) waterjet-assisted mechanical concrete cutting data. From these data, the correlation of concrete cutting and rock cutting will be made such that the rock-cutting methodology and data may be used in the most accurate way for predicting concrete-cutting characteristics.

b. Test Description

Three types of tests, waterjet kerfing, mechanical pick cutting and waterjet-assisted mechanical pick cutting have been conducted.

(1) Waterjet Kerfing Tests. Two pieces of concrete samples 12 by 12 by 6 inches, with properties the same as samples in pick cutting tests were used to conduct jet kerfing tests. The parameters used were:

(a) Standoff distance: 1 and 3 inches.

(b) Nozzle size: 0.016 inch and 0.024 inch.

(c) Waterjet pressure: 5,000, 10,000 and 20,000 psi.

(d) Jet traverse velocity: 15 inches to 45 inches per second.

The concrete samples were placed in the chuck of the lathe and rotated while the waterjet nozzle was clamped in the horizontal feed of the lathe. As the concrete made a revolution, the waterjet cut a slight spiral pass

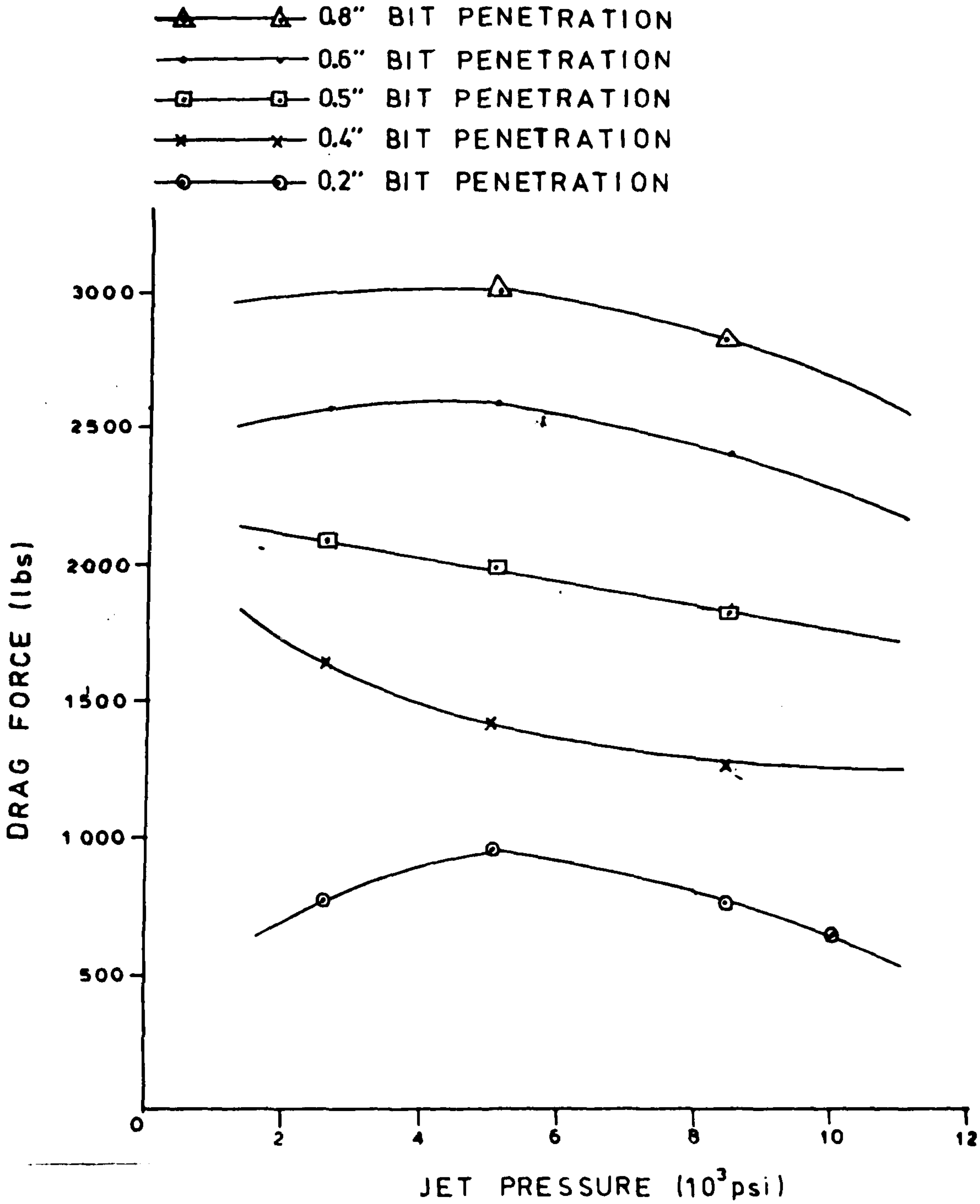


Figure C-5. Variation in Drag Cutting Forces, on Dakota Sandstone, With Waterjet Pressure. Jet Location 0.1 Inches in Front of Conical Bit.

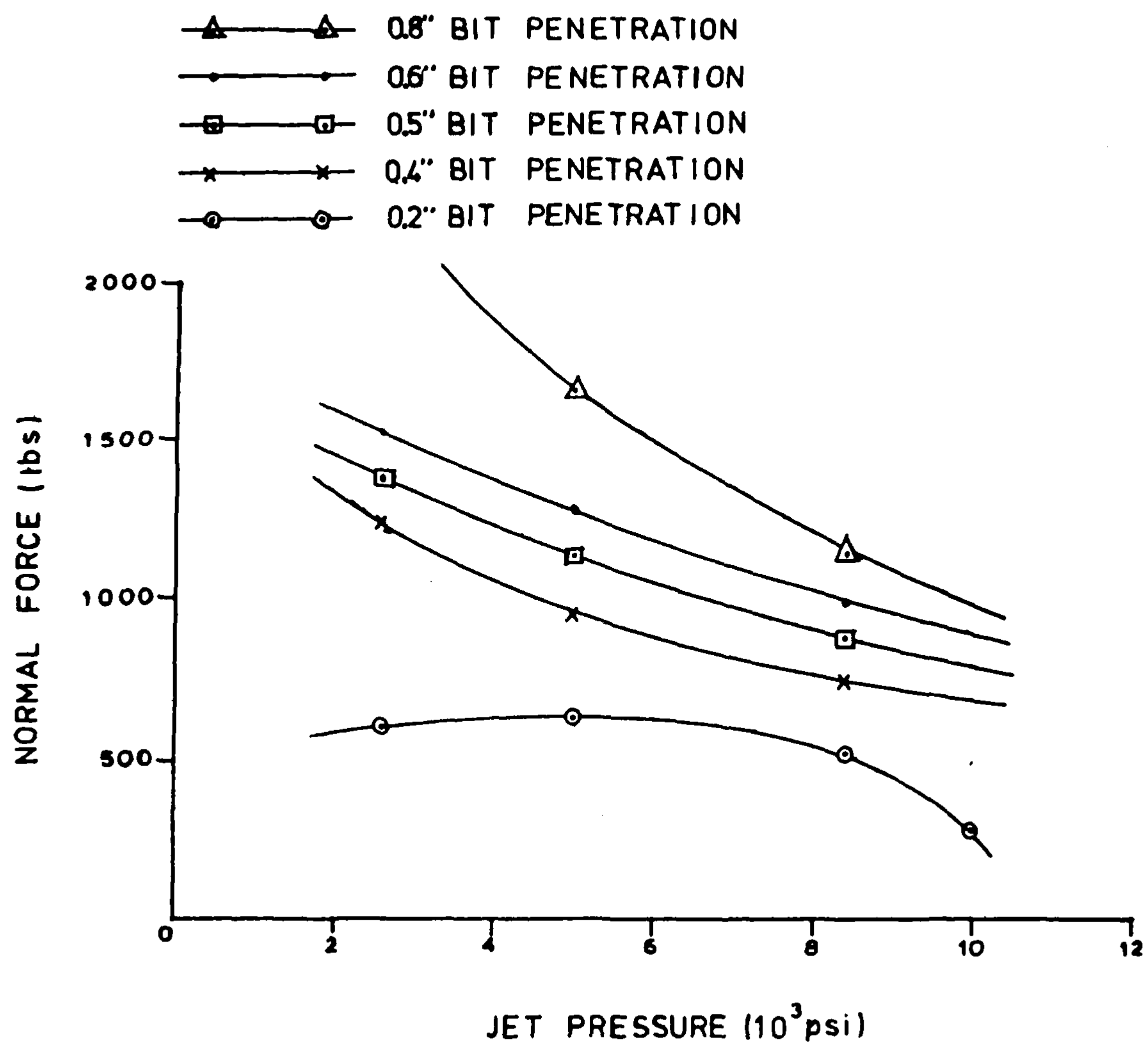


Figure C-6. Variation in Normal Cutting Forces, on Dakota Sandstone, With Waterjet Pressure. Jet Location 0.1 Inches in Front of Conical Bit.

with the feed between successive passes of .178 inch. The depth of the kerf was recorded to assess the effectiveness of the jet.

(2) Mechanical Pick Cutting Tests. The mechanical pick cutting tests were performed to obtain base data to assess the effectiveness of waterjet-assisted mechanical cutting through the reduction of cutting forces. The test parameters used were:

(a) Depth of cut: 1/2 and 3/4 inch.

(b) Spacing of cut: 1/2 and 1 inch.

(c) Traverse velocity: 20 and 32 inches per second.

(3) Waterjet-Assisted Mechanical Cutting Tests. A waterjet was positioned to impinge at a point 0.1 inch in front of the pick cutting in the direction of traverse. The parameters used were:

(a) Standoff distance: 1 inch.

(b) Nozzle size: 0.025 and 0.035 inch.

(c) Water pressure: 10,000 and 3,000 psi.

(d) Traverse velocity: 20 and 30 inches per second.

(e) Depth of cut: 0.5 and 0.75 inch.

(f) Spacing of cut: 0.5 and 1.0 inch.

c. Laboratory Tests

Several tasks were conducted in the laboratory: sample preparation, equipment calibration, linear cutting machine operation and testing in conjunction with waterjet operation and data collection. These tasks are described as the following.

(1) Sample Preparation. The concrete samples are mixes of Type 3A cement with granite gravel of less than 3/4-inch size and No. 400 sand with water-to-cement ratio of 0.49. The uniaxial compressive strength is 6,000 psi at 28 days. The detailed specifications and composition are listed in Table C-1. Two small samples of 12 by 12 by 6 inches were used for jet kerfing tests and the large sample of 24 by 24 by 30 inches was used for linear cutting tests.

(2) Calibration. Prior to cutting tests, the linear cutting machine was calibrated for its load-recording accuracy. A static test was performed by applying a known loading with a hydraulic ram to the pick cutter.

TABLE C-1. SPECIFICATIONS FOR CONCRETE TEST SAMPLE.

Designation	Cured Concrete w/Granite Aggregate
Sample Size	24" x 24" x 30"
Sample Composition:	
Type 3A Cement	1 part by Weight
Concrete Sand	1.9 part by weight
Georgian Mountain Stone Granite Aggregate	2.8 parts by weight
Water/Cement Ratio	0.47 by weight
Concrete Properties:	
ASTM Slump Value	2 inches maximum
28th Day Compressive Strength	6,000 pounds per square inch

Test samples were supplied by

Columbus Cement Products Co.
1165 Lum Creek Drive
Columbus, Ohio 43209
(615) 252-0955

The three forces, vertical, horizontal and side, resulting from the applied load and the orientation of the applied load were calibrated against the measured output from the strain gage bridges on the cutting head load cell. The load integrators were also calibrated with a known applied load.

(3) Linear Cutting Machine Operation and Testing. In all the tests, the bit was held at a set penetration depth into the concrete, and the thrust and drag forces resulting from moving the bit across the concrete were monitored. The pick forces on an individual bit varied greatly as the machine operated, while the penetration rate remained fairly constant because of the overall stiffness of the system.

The high bit concrete stresses produced by the bit cutting in concrete caused both chipping of the material and also induced microcracks. These microcracks affected the cutting forces on the bit and were dependent on the spacing between cuts and penetration depth. To reduce variability in the results from the effects of these cracks, the rock surfaces were conditioned with a series of initial cuts prior to a test run.

Two different cutting patterns were used to provide five types of cuts. The five types of cuts were: (1) first-gauge cut, (2) last-gauge cut, (3) zero relief cut, (4) one-side relief cut, and (5) two-side relief cut. The two cutting patterns, sequential and general, are based on the sequence of cuts. The sequential cuts were conducted by making individual cuts sequentially from left to right according to the cut number. Tests No. 1 through No. 6 (Figure C-7 and Figure C-8) are sequential cuts. The general sequence cuts were conducted by first making the gauge cut at the left hand side, then followed by making three successive cuts starting with the first cut at three spacings away and the two other cuts moving toward the relief (gauge) cut. Tests No. 7 through No. 16 are general sequence cuts (Figures C-9 and C-10).

A total of 16 tests were conducted with individual tests consisting of up to 16 cuts. These tests, along with the operating parameters, traverse velocity, spacing of cut, bit penetration, nozzle size, water pressure, and line number of cut types, are listed in Table C-2.

(4) Waterjet Operation. The waterjet nozzle assembly was mounted on the bit mounting plate in an orientation with the waterjet at a 90-degree angle relative to the cutting axis of the bit. This was done by using slip-type swivel joints to allow exact positioning of the nozzle. The jet was positioned and tested under pressure so that the waterjet was aligned with the cutting pick.

In making the waterjet-assisted cuts, the concrete was positioned in front of the bit and nozzle. Then the waterjet was turned on and the concrete pushed toward the bit. Upon completion of the cut, the jet was turned off and the concrete pulled back. The concrete sample was then

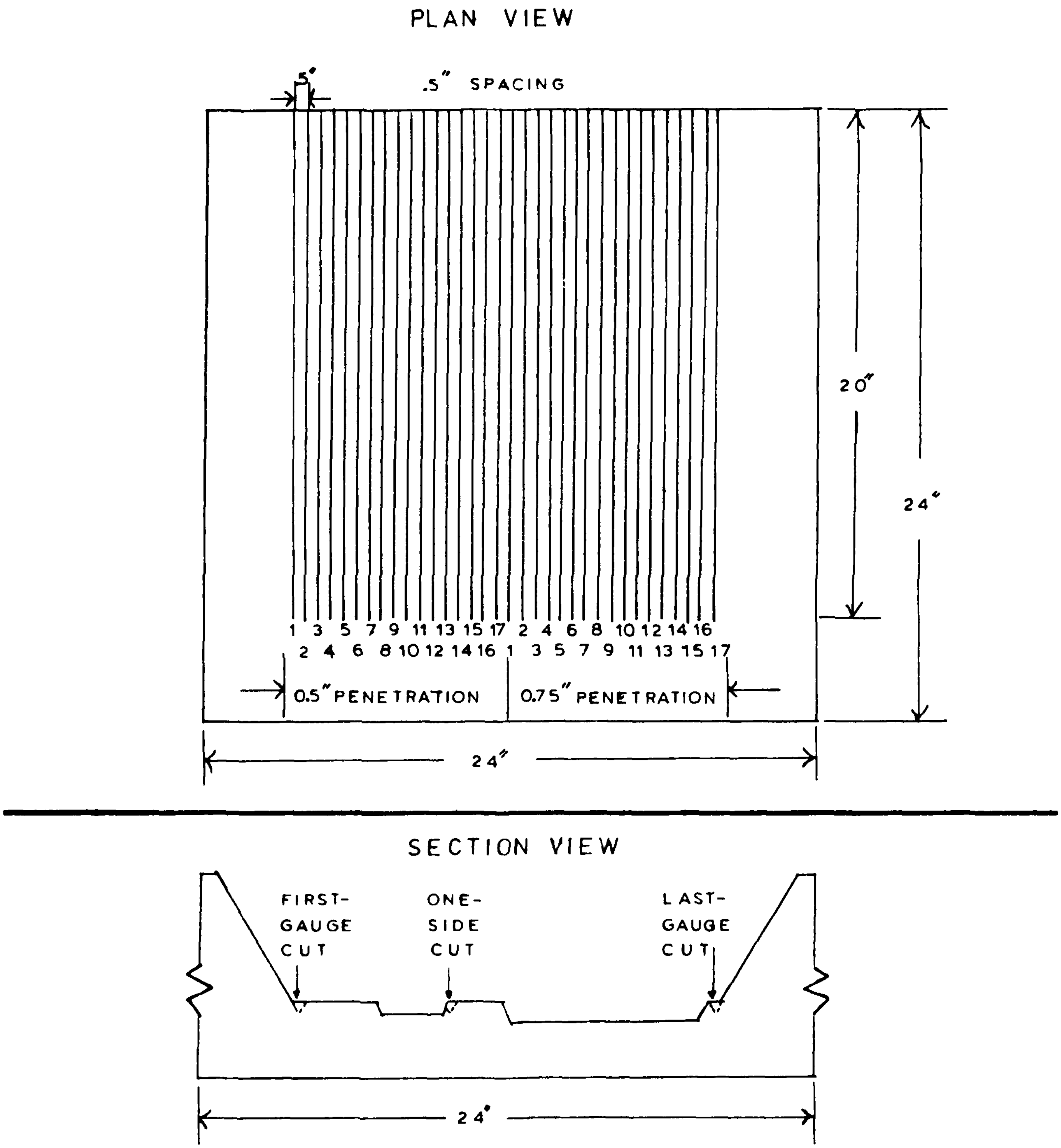


Figure C-7. Test Pattern: Test No.1 Through No.4.

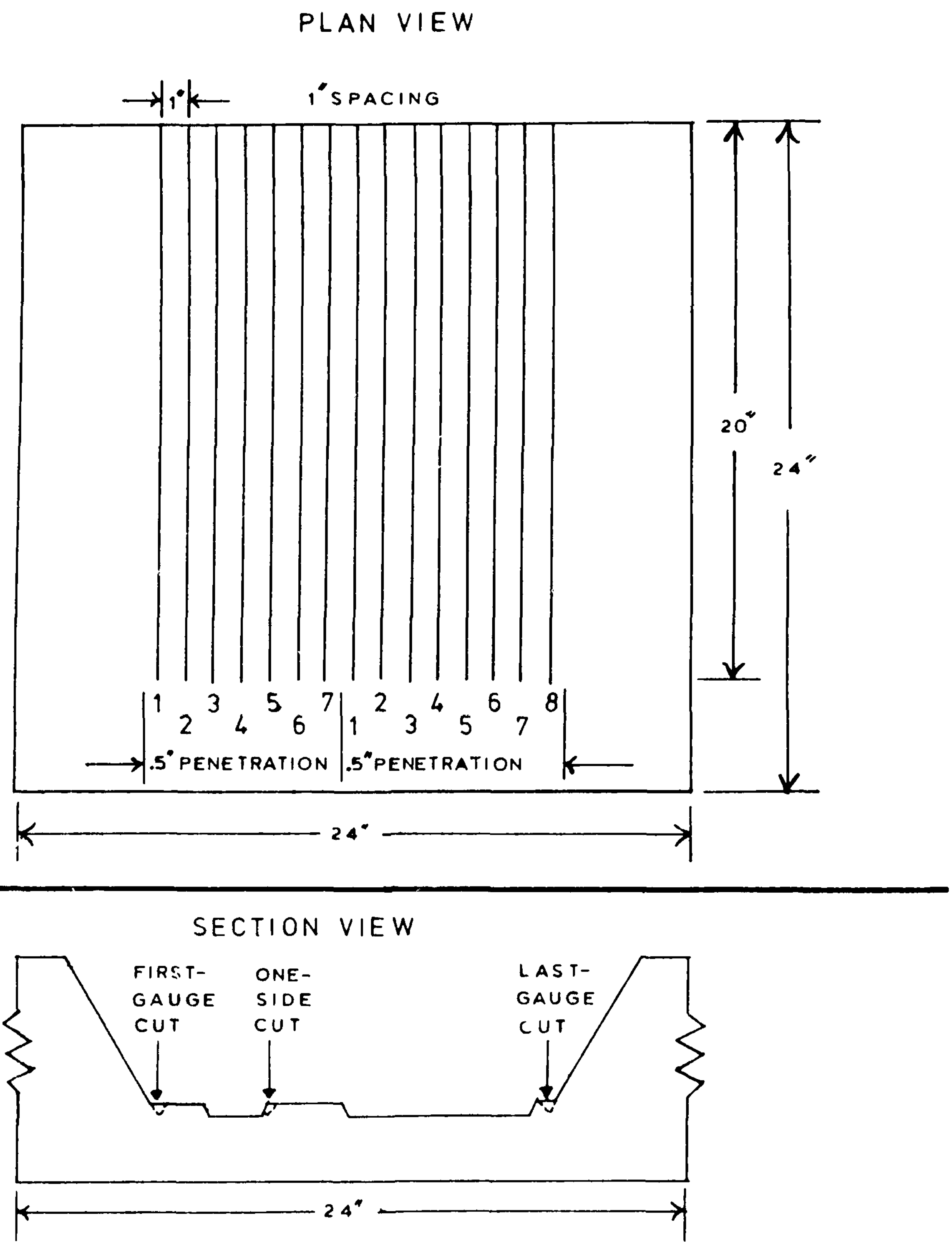


Figure C-8. Test Pattern: Test No.5 Through No.6.

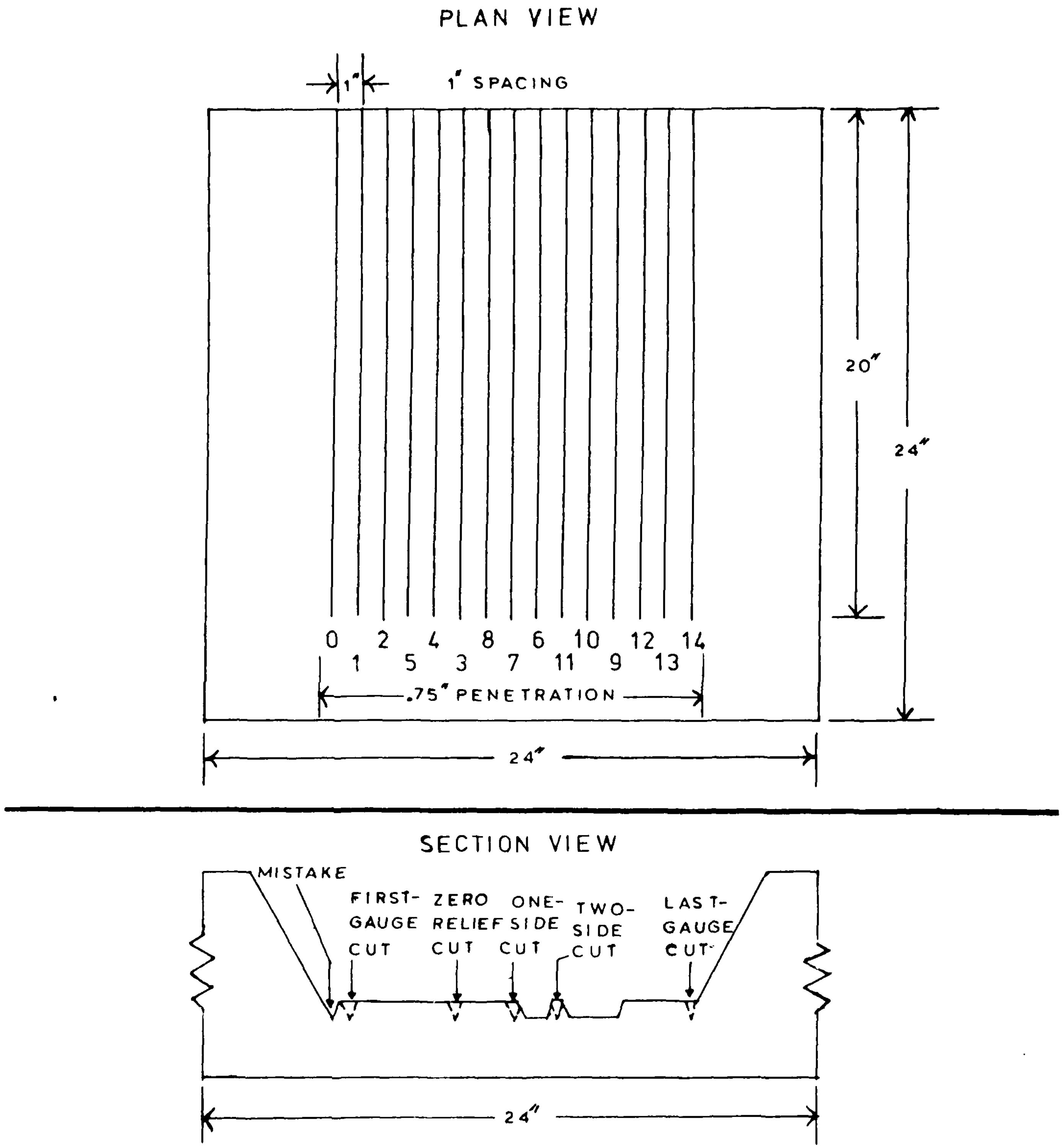


Figure C-9. Test Pattern: Test No.7 Through No.8.

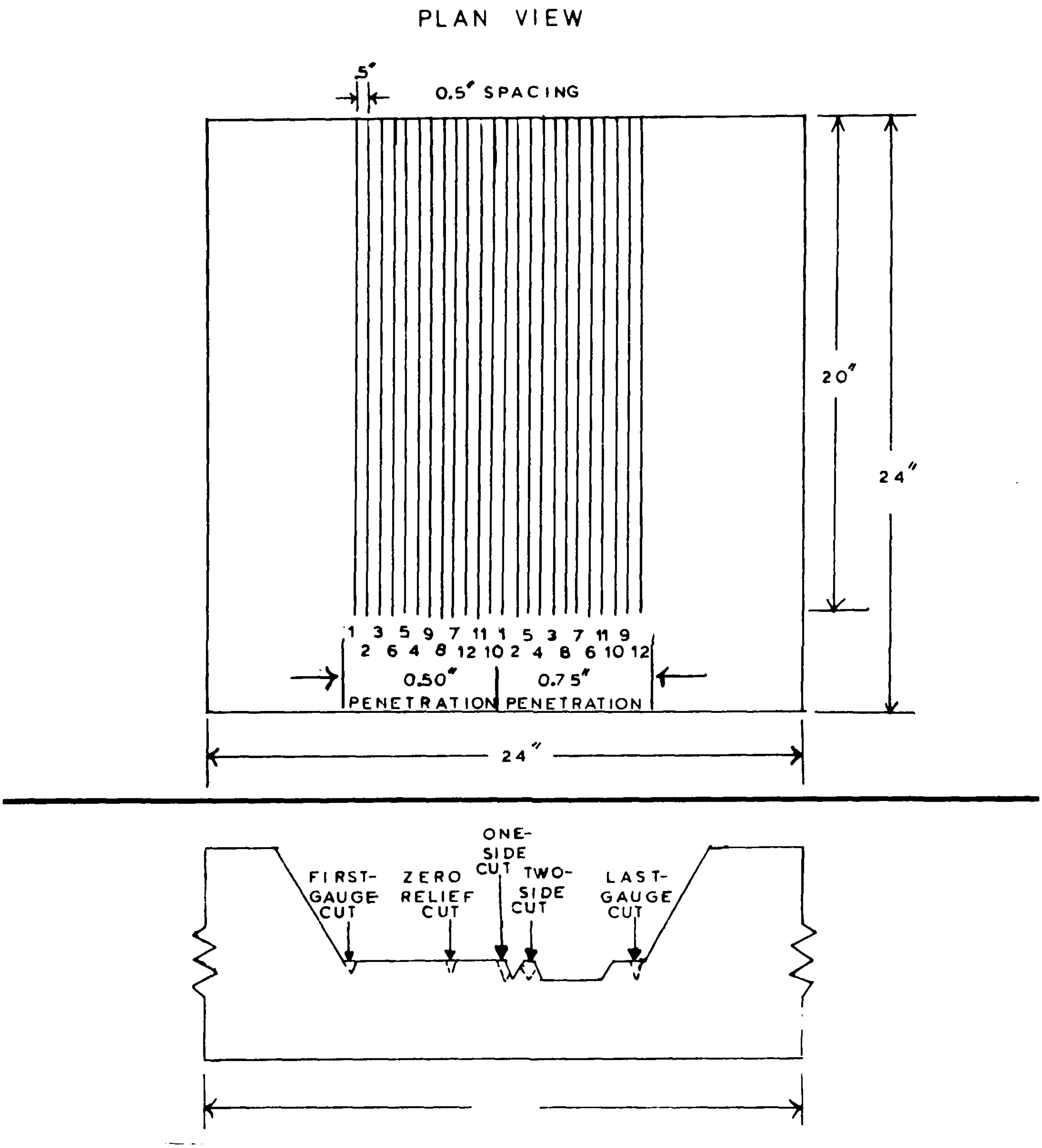


Figure C-10. Test Pattern: Test No.9 Through No.11.

TABLE C-2. CUTTING TEST DATA.

TEST No.	REF. FIGURE	TYPE OF CUT	SPEED (ips)	SPACING (Inches)	PENETRATION (Inches)	NOZZLE ORIFICE (Inches)	WATER PRESSURE (psi)	LINE NUMBER OF CUT TYPES				
								FIRST GAUGE	LAST GAUGE	ZERO RELIEF	ONE SIDE RELIEF	TWO SIDE RELIEF
1		DRY (SEQ)	20	0.5	.50	NA	NA	1	17	-------	2 TO 16	---------
2		DRY (SEQ)	32	0.5	.50	NA	NA	1	16	-------	2 TO 15	---------
3		DRY (SEQ)	20	0.5	.75	NA	NA	1	16	-------	2 TO 15	---------
4		DRY (SEQ)	32	0.5	.75	NA	NA	1	16	-------	2 TO 15	---------
5		DRY (SEQ)	20	1.0	.50	NA	NA	1	7	-------	2 TO 6	---------
6		DRY (SEQ)	32	1.0	.50	NA	NA	1	8	-------	2 TO 7	---------
7		DRY (GEN)	20	1.0	.75	NA	NA	1	14	5,8,11	2,4,7,10 12,13	3,6,9
8		DRY (GEN)	32	1.0	.75	NA	NA	1	14	5,8,11	2,4,7,10 12,13	3,6,9
9		WET (GEN)	20	0.5	.50	.025	10,000	1	13	6,9,12	2,3,5,8, 11	4,7,10
10		WET (GEN)	32	0.5	.50	.025	10,000	1	12	6,9	2,3,5,8, 11	4,7,10
11		WET (GEN)	20	0.5	.75	.025	10,000	1	12	5,8,11	2,4,7,10	3,6,9
12		WET (GEN)	32	0.5	.75	.025	10,000	1	11	5,8	2,4,7,10	3,6,9
13		WET (GEN)	20	1.0	.50	.025	10,000	1	14	5,8,11,13	2,4,7,10	3,6,9,12
14		WET (GEN)	32	1.0	.50	.035	3,000	1	17	5,8,11,14	2,4,7,10 13,16	3,6,9,12 15
15		WET (GEN)	20	1.0	.75	.035	3,000	1	15	5,8,11,14	2,4,7,10 13	3,6,9,12
16		WET (GEN)	32	1.0	.75	.035	3,000	1	14	5,8,11	2,4,7,10 13	3,6,9,12

(SEQ): SEQUENTIAL CUT

(GEN): GENERAL SEQUENCE OF CUT

shifted laterally to the desired spacing between cuts and the procedure was repeated.

(5) Data Collection. The data for the vertical, drag, and side forces on the bit were collected and integrated electronically to provide a total force per cut for each of the three directions. The depth of cut, the cutting speed, water pressure, and spacing of the cut were recorded on each cut.

d. Equipment

The equipment used in the test program consisted of four major components: (1) the drag bit and its mounting block and load cells; (2) the linear rock cutting machine, including the main frame and sample box with a hydraulic ram for linear translation; (3) the instrumentation to monitor the forces required to cut the concrete; and (4) the high-pressure waterjet system (Figures C-11 and C-12).

(1) Drag Bits. The pointed conical or plumb bob-type pick cutter (Figures C-13 and C-14) was used for concrete cutting. A tungsten carbide insert was attached at the tip. This bit was designed for mounting at a 45-degree angle to the concrete surface and was designed to freely rotate axially in its mounting so that the tip is self-sharpening and maintains a constant cutting profile.

The pick cutter was attached to the mounting block, which was rigidly fastened to the underside of the load cell on the linear rock cutter used to measure the normal and drag forces.

(2) Linear Cutting Machine. This unit supports the concrete sample and the cutting tool, and controls the interaction between them. The unit is designed to test full-sized rock cutters under actual loading conditions and can withstand large dynamic loads with minimal deflection or vibration. A stationary overhead frame holds the cutting tool while the concrete sample below is driven horizontally into the pick cutter.

The main frame consists of large, welded and bolted steel beams. The cutting tool is suspended under the large boxed crossbeams and can be raised or lowered by a hydraulic ram that is mounted to the top of the runs through the beam. Steel plate spacers are placed between the cutter mounting and the crossbeam so that a constant cutter height can be maintained. Calibration experiments showed that a 25,000-pound load on the cutter produced less than 0.01 inch deflection on the frame. The sample box, fabricated from I-beams, is positioned horizontally beneath the cutter and moves horizontally on two 3-inch diameter steel rails anchored to the floor. Four linear bearings provide a rigid, low-friction mount.

Horizontal thrust is provided by a servo-controlled hydraulic ram that can provide 30,000 pounds of force at 40 inches per second feed rate (180 horsepower) over a 5-foot stroke. To index the cutting

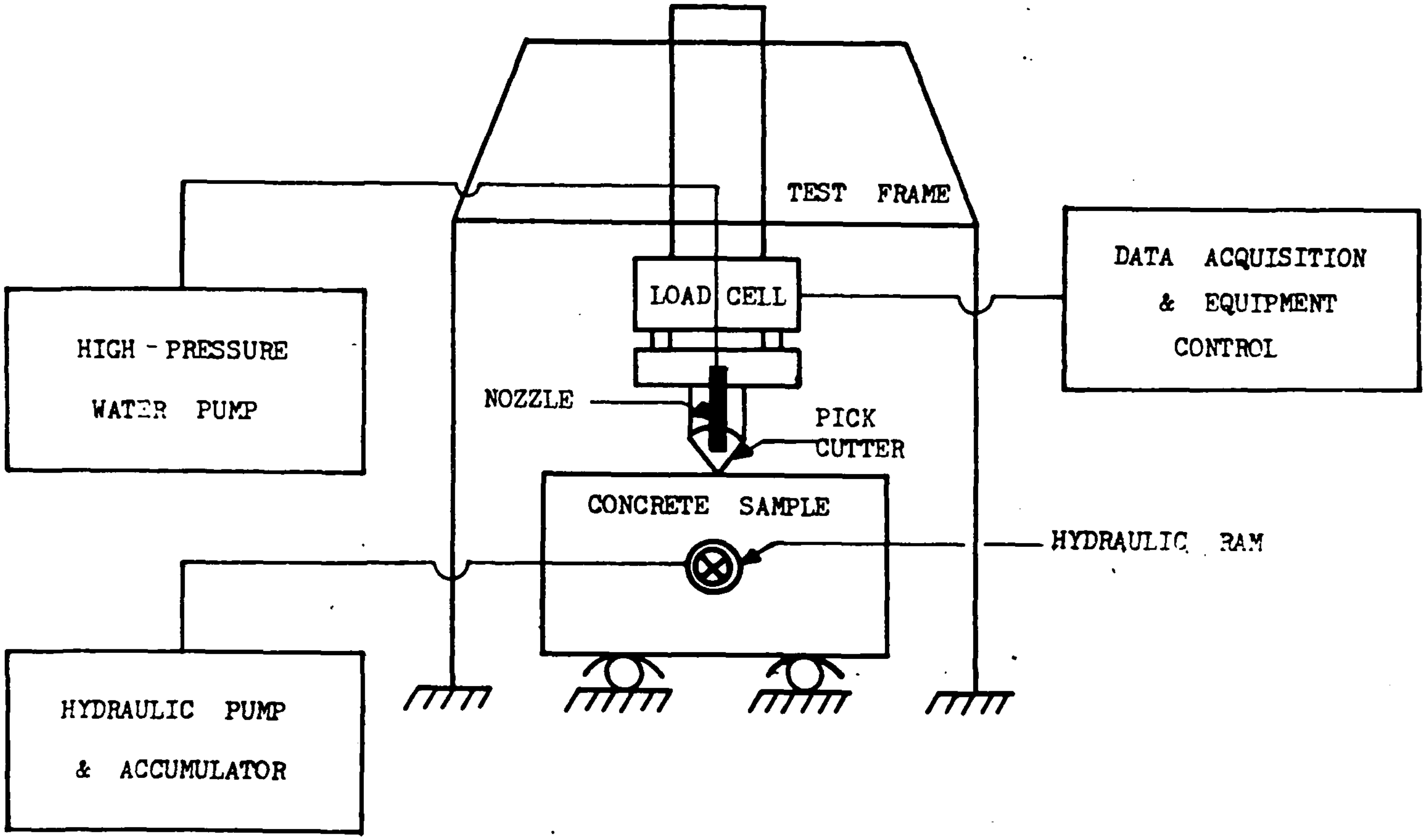


Figure C-11. Schematic of Waterjet-Assisted Mechanical Cutting Equipment and Instrumentation (View Along Cutting Axes).

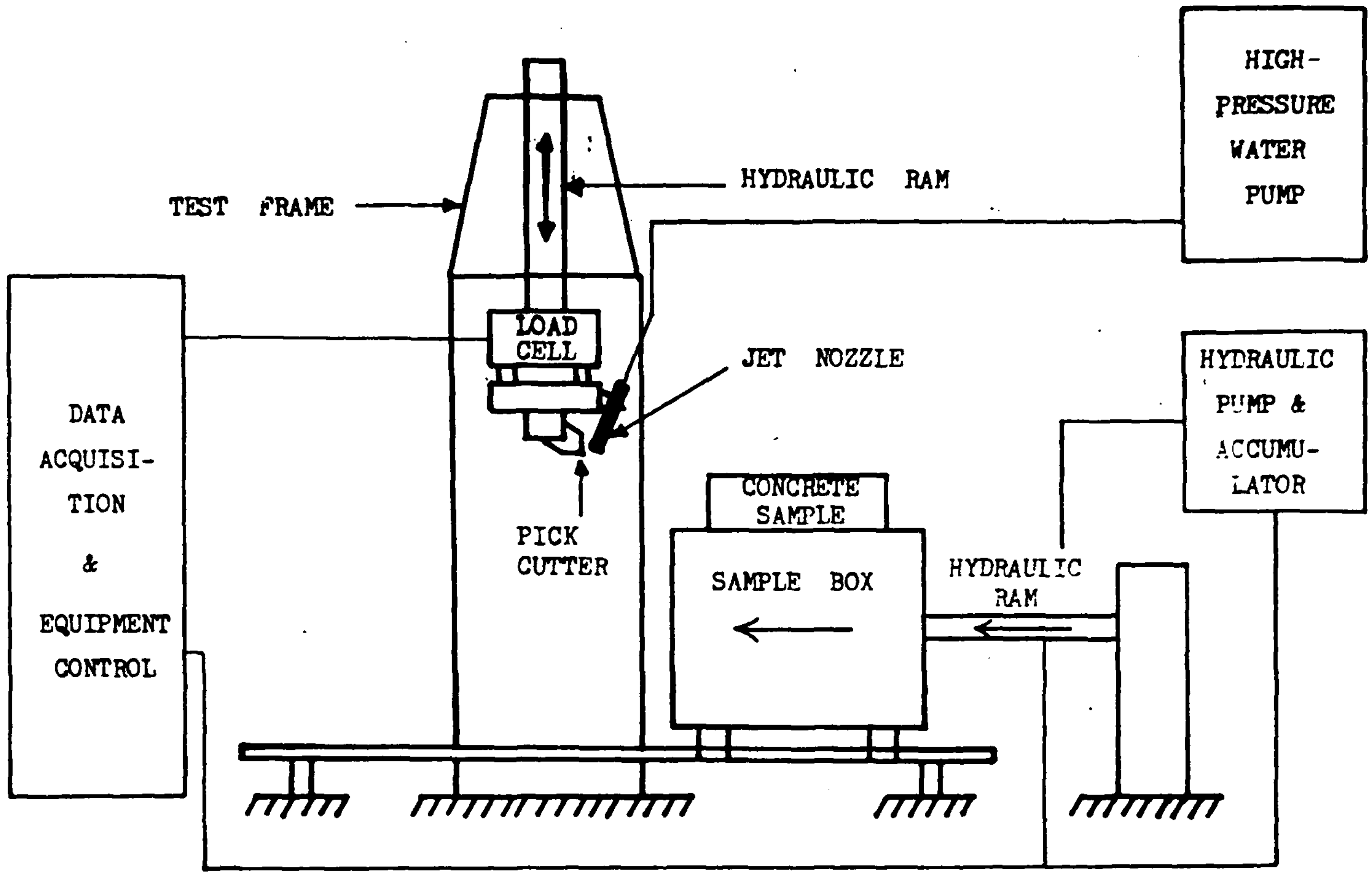


Figure C-12. Schematic of Waterjet-Assisted Mechanical Cutting Equipment and Instrumentation (Side View).

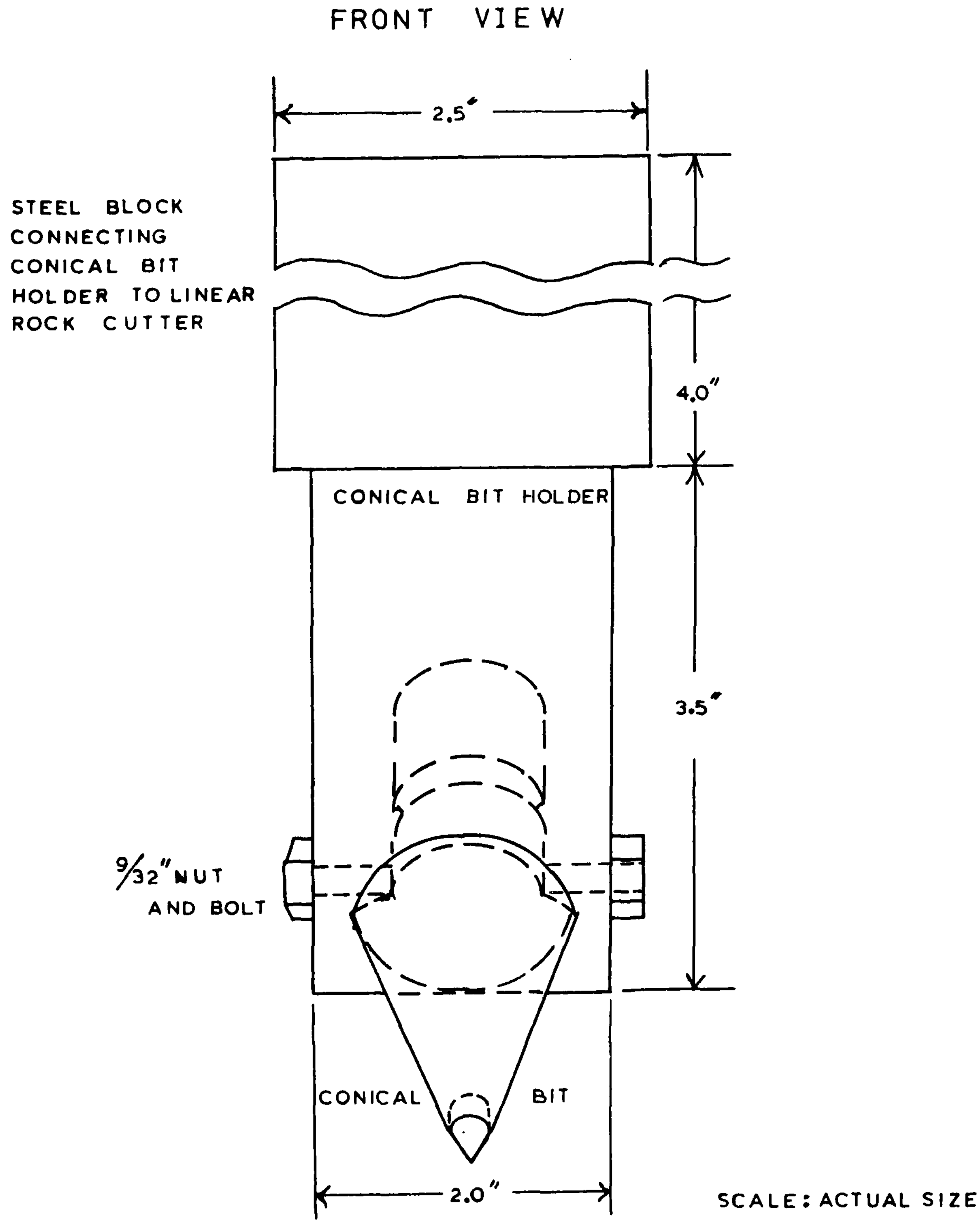


Figure C-13. Conical Bit Holder Used in Testing With the Linear Rock Cutter.

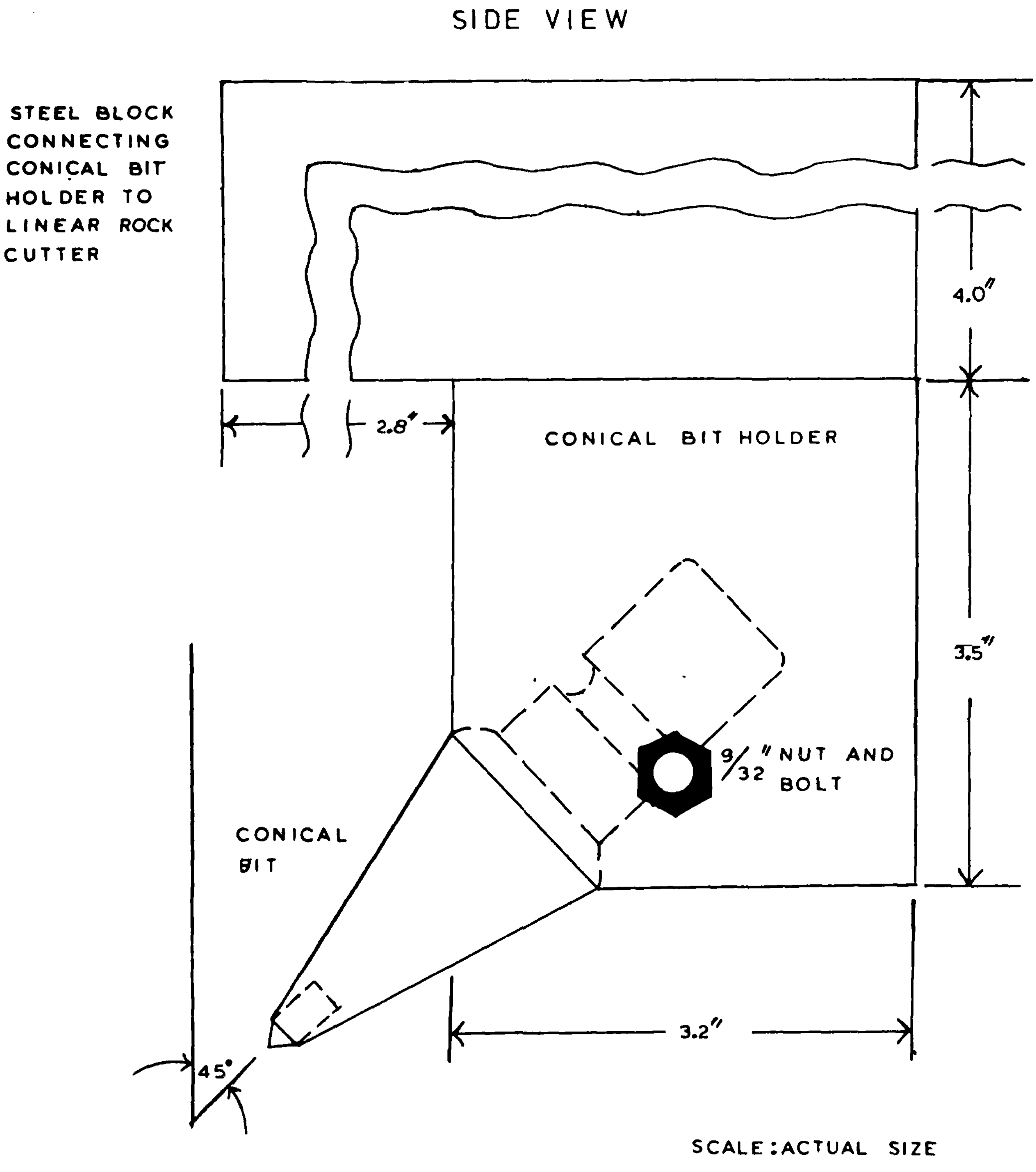


Figure C-14. Conical Bit Holder Used in Testing With the Linear Rock Cutter.

paths, a pair of 2-foot stroke double-acting cylinders move the concrete holder box sideways.

(3) Force Monitoring System. This unit consists of signal conditioners and a digital integrator that determines the average values for the normal, drag, and side forces on the cutter. The triaxial load cell consists of two thick aluminum plates separated by four pressured, hollow aluminum cylinders on whose circumferences are mounted six dual-element strain gauges. The gauges are wired into three full-bridge circuits, one for each principal load direction. Calibration tests show that there is less than 2 percent cross-talk between the circuits. For the planned test, the drag bit is to be mounted with its cutting points in a vertical plane passing through the center line of the load cell so that the thrust force on the bits is purely compressive. The side and drag forces on the bits produce moments on the load cell about two orthogonal axes. Strain gauge excitation and signal amplification are provided by three separate signal conditioners. A steady 10-volt input is supplied to each bridge. The output from each bridge is channeled through a 100 to 2,000 variable gain amplifier. The amplified signals are digitized at 1,000 readings per second, and an integrator sums the digital values and provides a four-digit readout for the total force per cut for each channel. Three digitized values are divided by the elapsed time per cut to give the average force. Peak force values during the cut are also obtained. A microswitch located on the thrust ram is adjusted for the particular cut length, and controls the integration circuits.

(4) Waterjet System. This unit consists of a high-pressure pump, a pressure regulator, and a nozzle assembly. The pump is a commercially available unit.

A hydroblaster Model 610 pump with lower (4.5 gpm) flow is to be used for the planned tests. The unit consists of a small six-cylinder axial piston pump powered by a 20-horsepower electric motor. The constant displacement output could produce up to 12,000 psi pressure. A 0.5-inch diameter steel braided hose connects the pump to the nozzle.

The pressure regulator consists of a screw-controlled compression spring forcing a needle into the orifice of a tee coupling. Changing the spring force regulates the quantity of flow allowed to bypass the needle. A second needle valve in the delivery line controls the flow to the nozzle.

4. TEST DATA ANALYSIS

a. General

Typical forces for various cuts along a cutting surface for dry and wet cuts are shown in Figures C-15 and C-16, respectively. As shown, the first-gauge cut on the left-hand side tends to have the highest vertical and horizontal forces and perhaps the least side force due to the

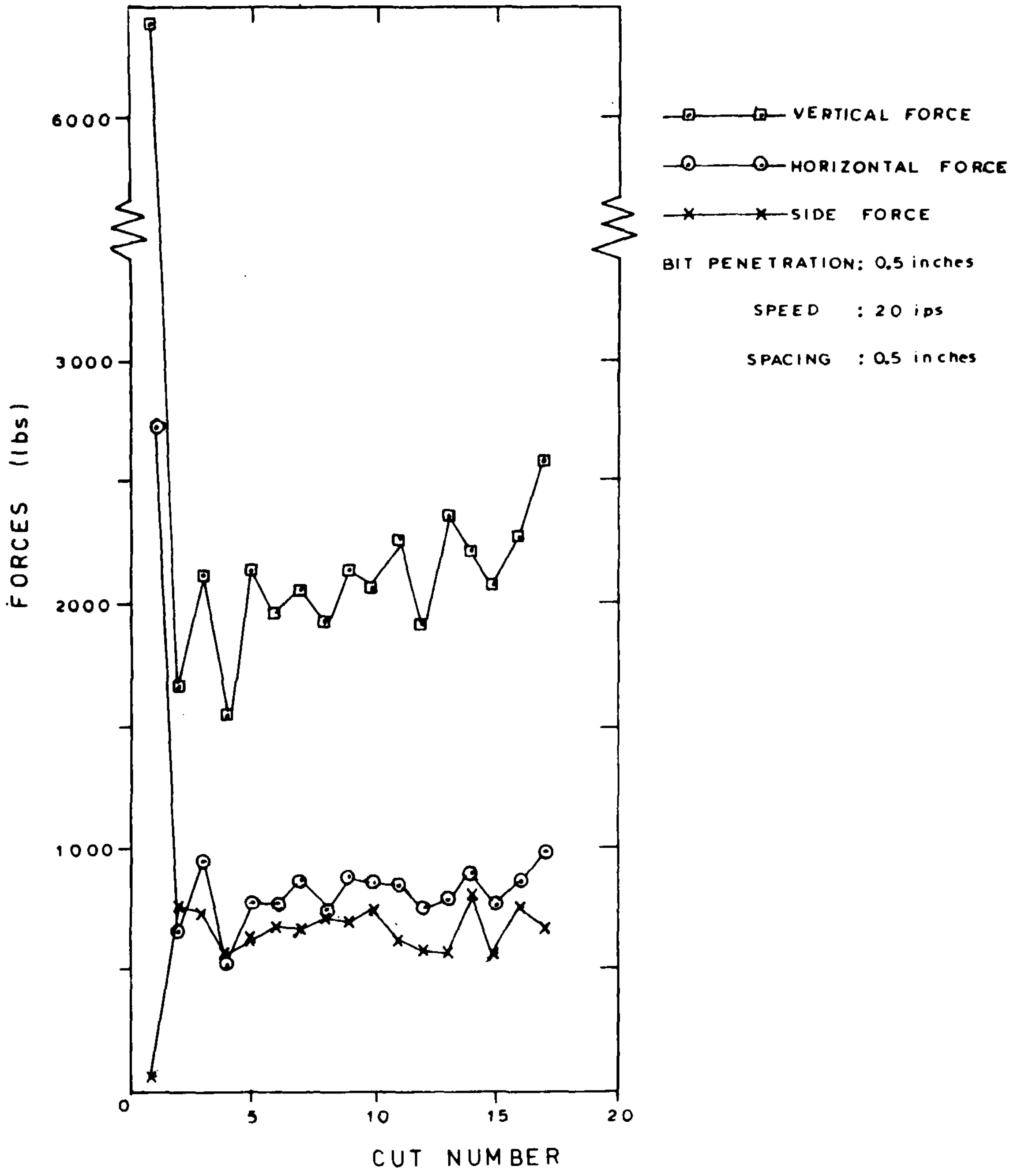


Figure C-15. Forces vs. Cut Number For Test No.1 - Dry Cut.

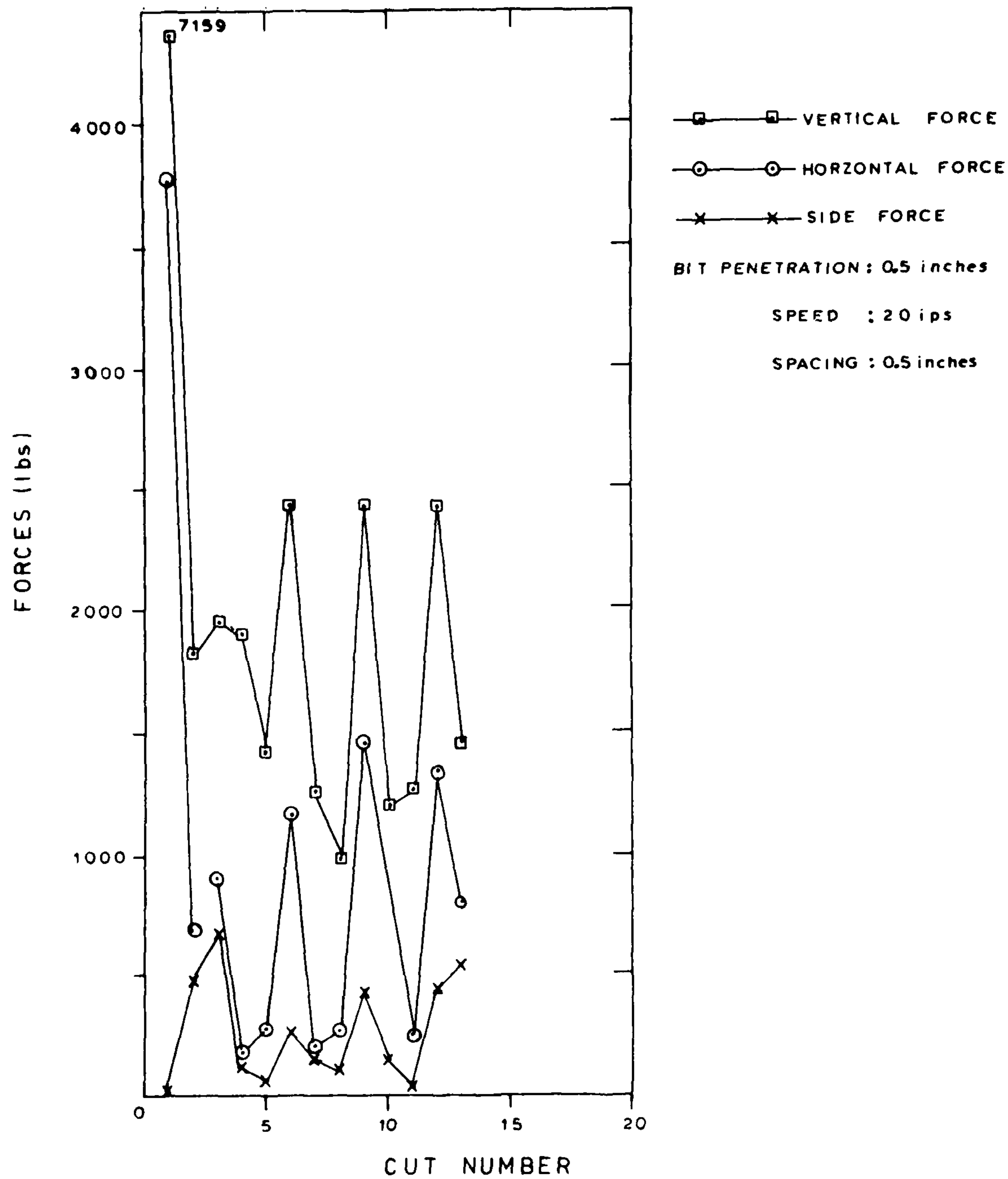


Figure C-16. Forces vs. Cut Number For Test No.9 - Wet Cut.

balanced cutting geometry. The zero relief cut generally has the next largest force. The one-side and two-side relief cuts have the smallest forces with the one-side relief being generally higher (Figure C-17).

The total of 16 tests consisted of 108 dry and 108 wet cuts. The types of cuts and the distribution of dry and wet cuts are listed in Table C-3. The majority of tests are one-side relief cuts which consist of 96 dry and 38 wet cuts, or 85 and 35 percent, respectively, for all the cuts in the dry and wet categories. For slot cutting, the picks experience cutting situations that are most frequently similar to the one-side cuts, less frequently like zero relief cuts and even fewer with two-side relief cuts.

b. One-Side Relief Cut

All the one-side relief cut results are plotted in Figures C-18, C-19, and C-20 for vertical, horizontal and side forces at 0.5 and 0.75 inch depth of cuts with 1 and 0.5 inch spacing and 32 and 20 inches per second traverse velocity. It clearly shows that all the wet cuts have lower forces than dry cuts with the same spacing and traverse velocity. The higher velocity (32 ips) cuts generally have higher forces than the low velocity (20 ips) cuts. At the same time, the wider spaced cuts (1 inch spacing) have higher forces than the narrower spaced (0.5 inch) cuts.

The average cutting forces for all the tests at the two penetrations for both dry and wet cuts are shown on Figure C-21 for the averge vertical forces, Figure C-22 for average horizontal forces, and Figure C-23 for the average side forces. These figures indicate clearly that the waterjet can reduce 30 to 50 percent of the vertical force, 20 to 40 percent of the horizontal force, and about 60 percent of the side forces. The waterjet seems to be more effective at deeper cuts of 0.75 inch, than the shallower cuts of 0.5 inch. This is because the microcracks created under a deeper cut are wider and longer than the shallow cuts. Therefore, the hydrofracturing mechanism from the high-pressure water is more pronounced in fracturing the concrete, thus reducing the cutting forces.

c. Zero Relief Cut

The vertical, horizontal and side forces at 0.5-and 0.75-inch depth of cuts with 0.5-and 1-inch spacing and 20 and 32 inches per second traverse are shown in Figures C-24, C-25, and C-26, respectively. In comparing the dry and wet cuts, it is generally concluded that the wet cuts have lower forces than the dry cuts. However, the effects of cut spacing and traverse velocity seem to be mixed. No firm trend can be established.

The average forces at 0.5- and 0.75-inch penetration are shown in Figures C-27, C-28, and C-29. There is a clear trend of the vertical force reduction from the waterjet. However, the average horizontal and average side forces essentially showed no effect by the waterjet. This explains the mixed trend in the previous set of results as in Figures C-25 and C-26.

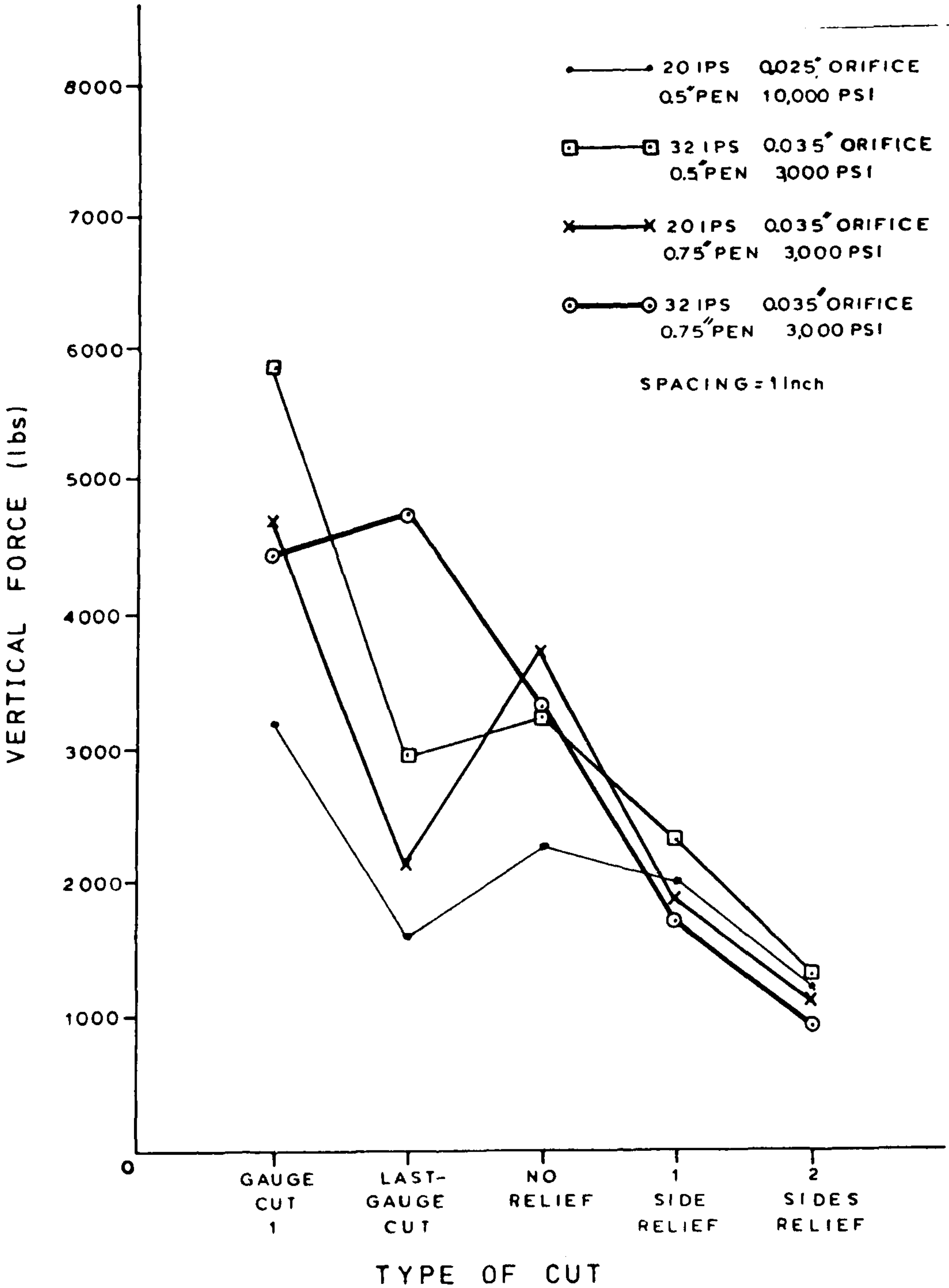


Figure C-17. Vertical Force vs. Type of Cut With Waterjet.

TABLE C-3. DISTRIBUTION OF THE VARIOUS TYPES OF CUTS.

(a)

TYPE OF CUT	NUMBER OF CUTS		
	DRY	WET	TOTAL
First-Gauge Cut	8	8	16
Last-Gauge Cut	8	8	16
Zero-Side Relief Cut	0*	25	25
One-Side Relief Cut	92	38	130
Two-Side Relief Cut	0	29	29
Total Number of Cuts	108	108	216

(b)

TYPE OF CUT	PERCENT OF TOTAL CUTS		
	DRY (%)	WET (%)	TOTAL (%)
First-Gauge Cut	7.4	7.4	7.4
Last-Gauge Cut	7.4	7.4	7.4
Zero-Side Relief Cut	0.0*	23.2	11.6
One-Side Relief Cut	85.2	35.2	60.2
Two-Side Relief Cut	0.0	26.8	13.4
Total Percentage of Cuts	100.0%	100.0%	100.0%

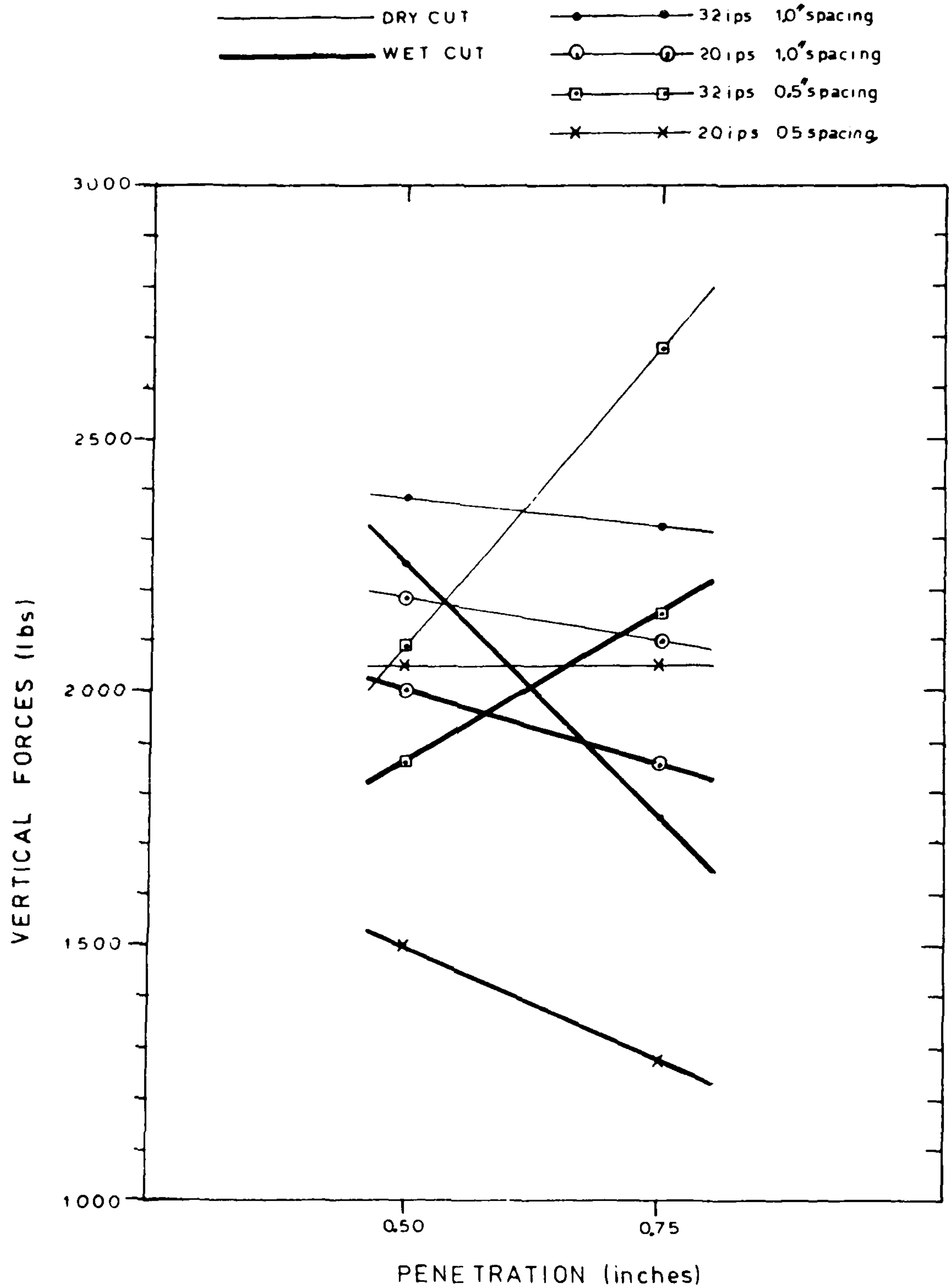


Figure C-18. Vertical Forces vs. Penetration Depth For One-Side Cut.

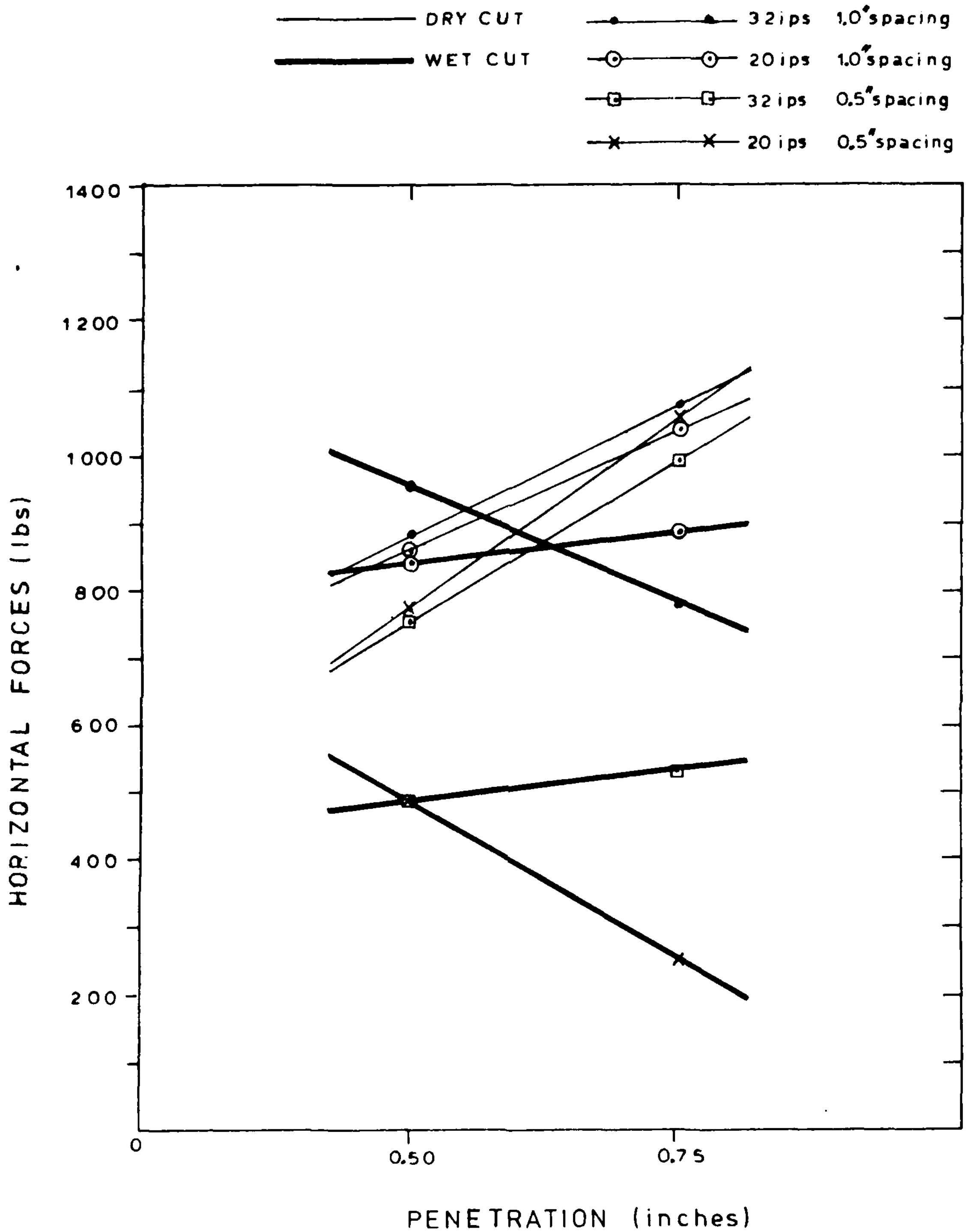


Figure C-19. Horizontal Forces vs. Penetration Depth For One-Side Cut.

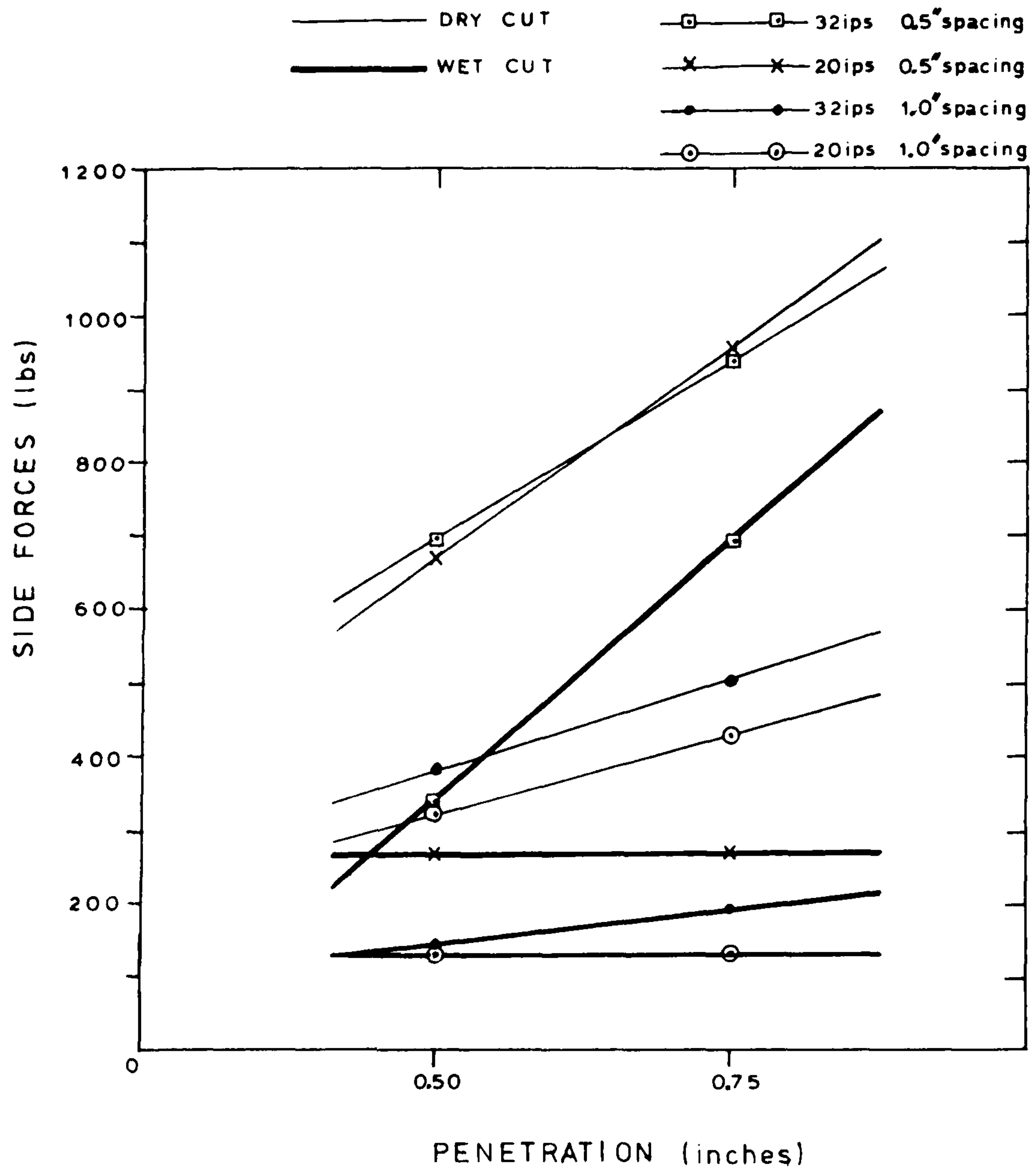


Figure C-20. Side Forces vs. Penetration Depth For One-Side Cut.

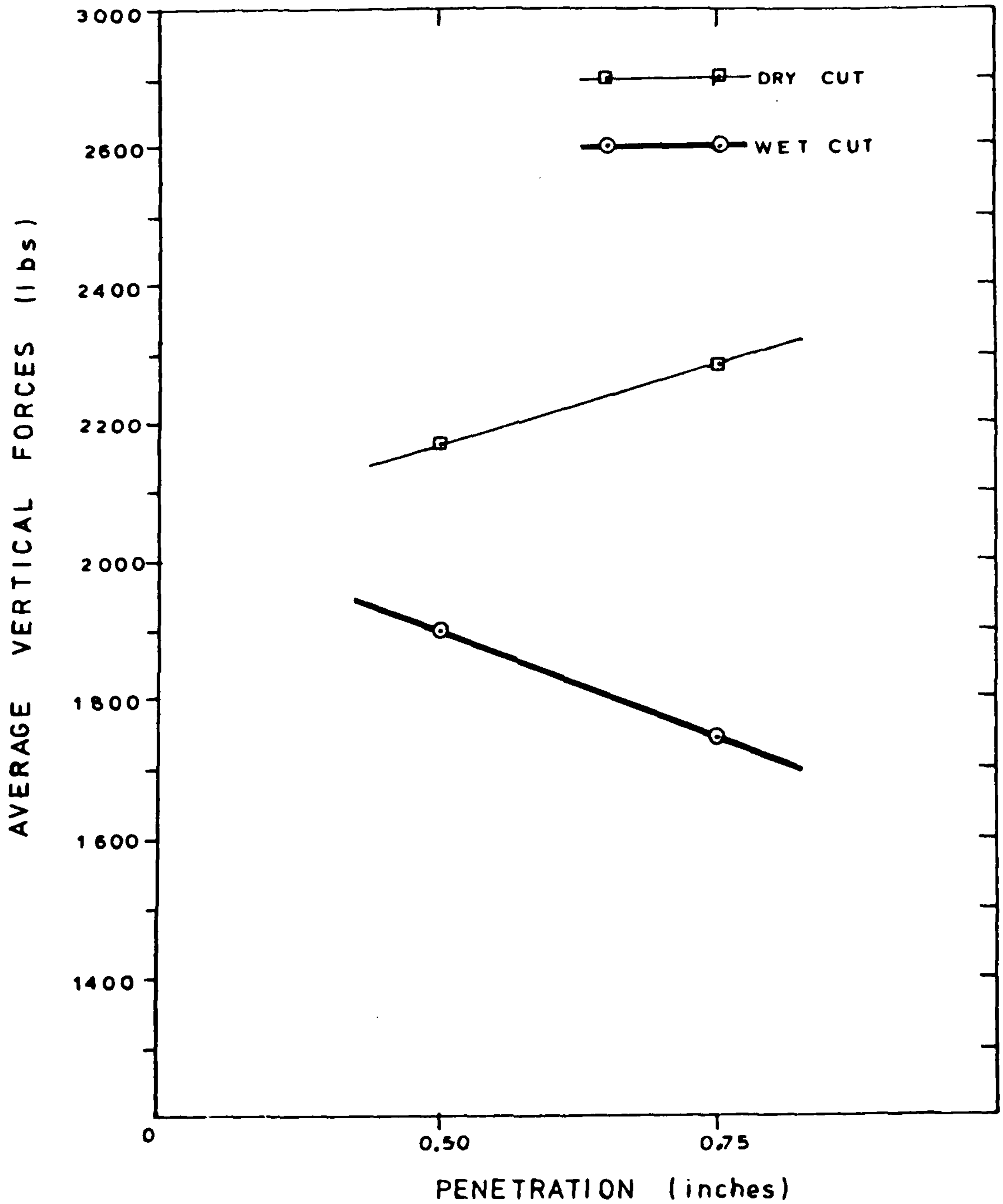


Figure C-21. Average Vertical Forces vs. Penetration Depth For One-Side Cut.

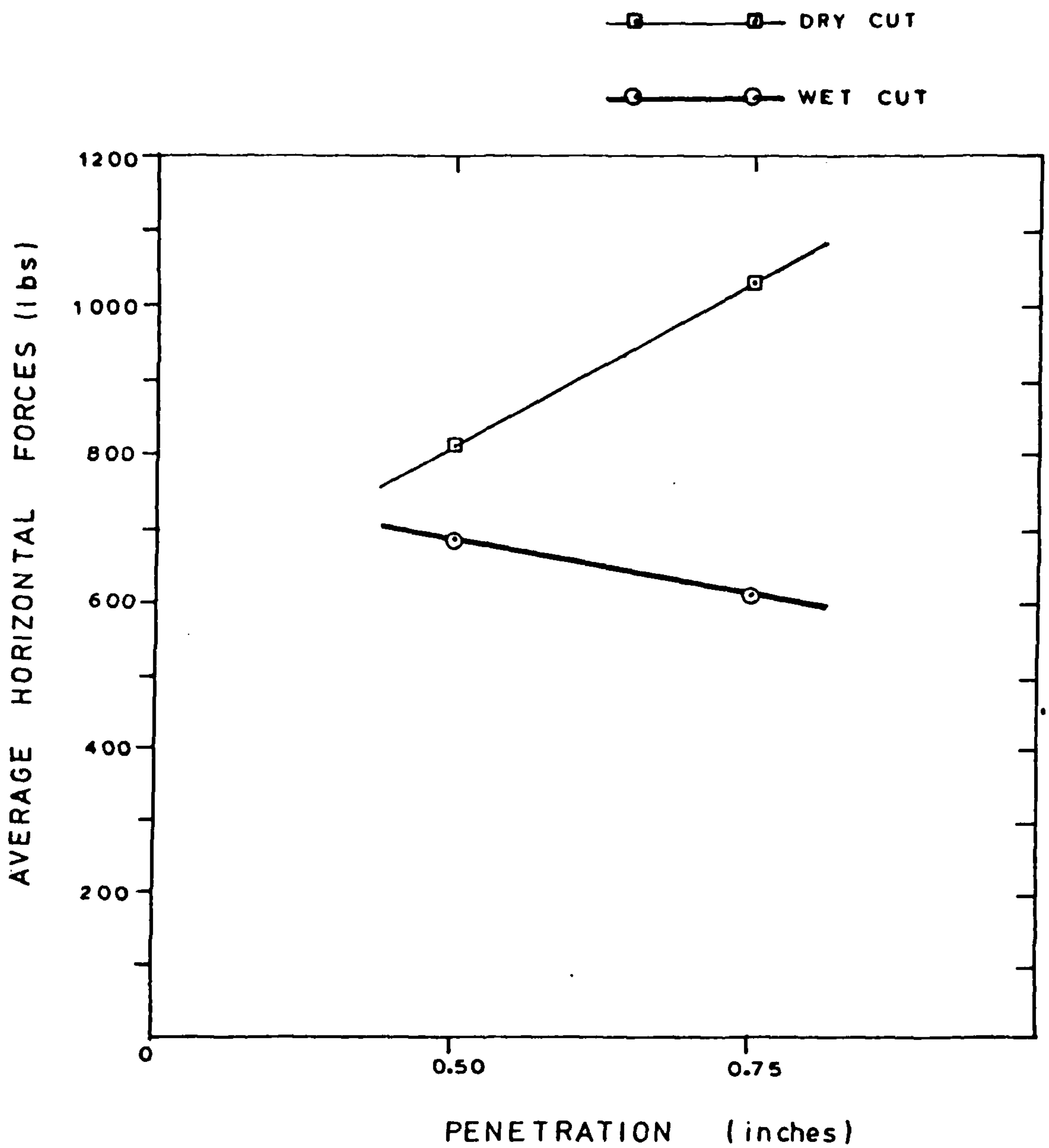


Figure C-22. Average Horizontal Forces vs. Penetration Depth For One-Side Cut.

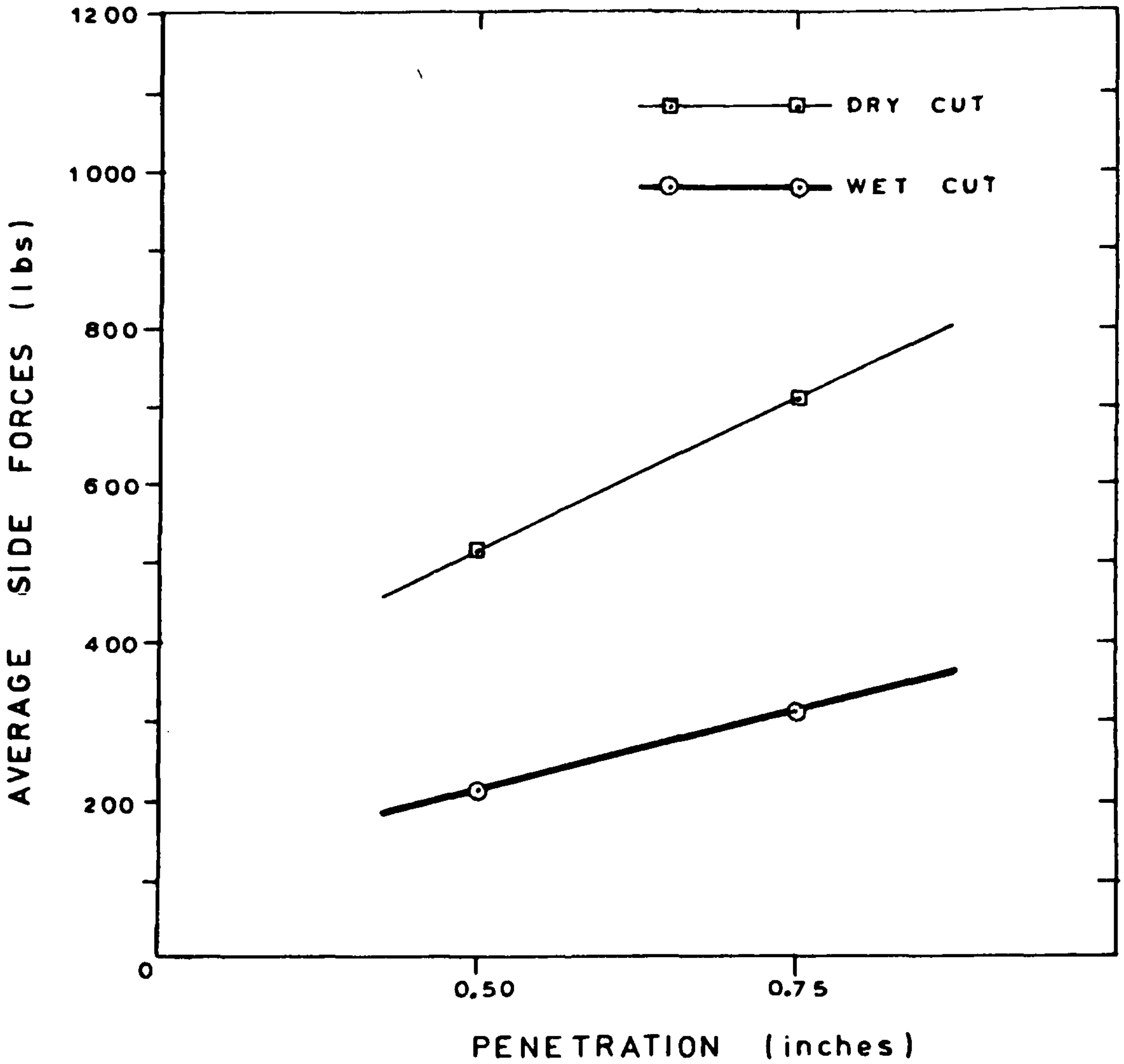


Figure C-23. Average Side Forces vs. Penetration Depth For One-Side Cut.

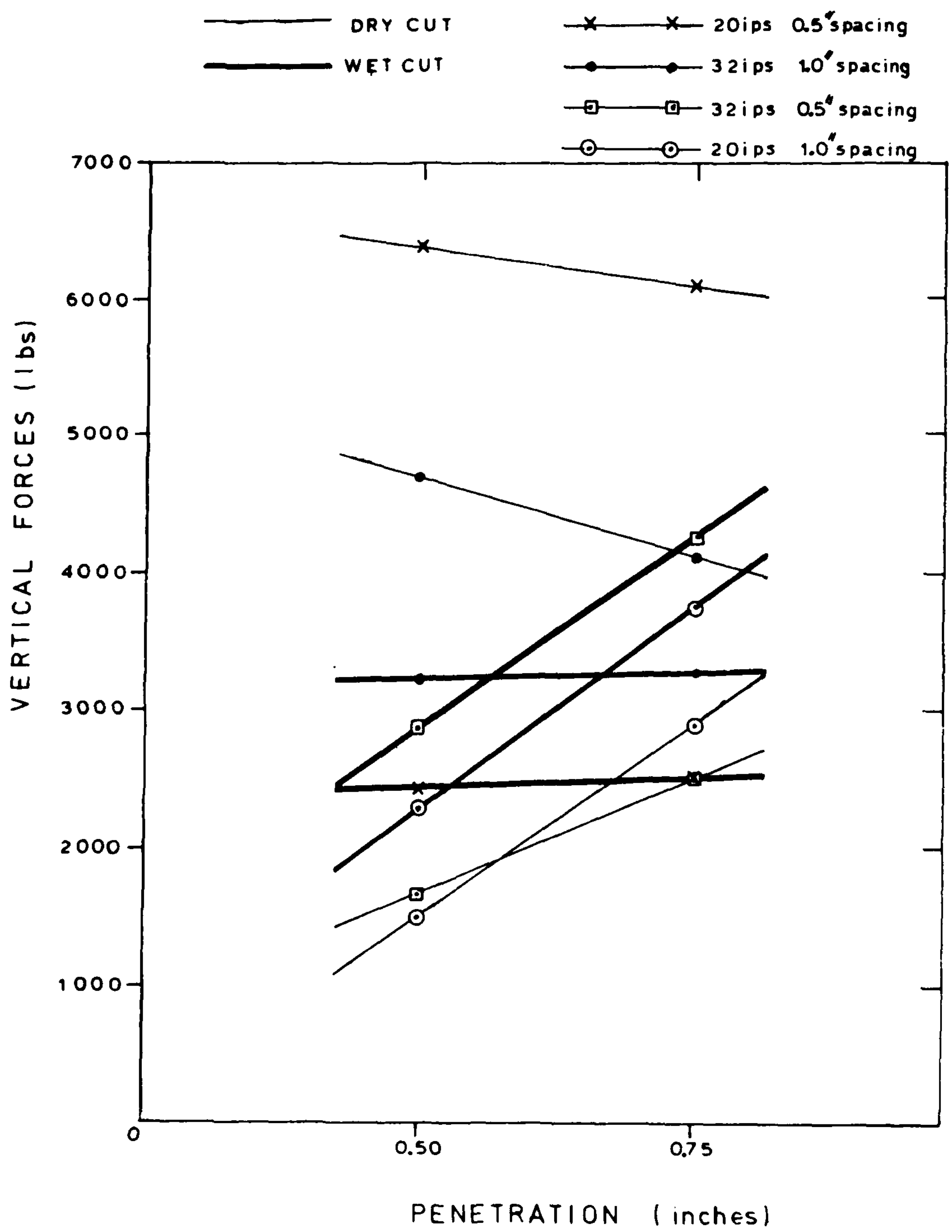


Figure C-24. Vertical Forces vs. Penetration Depth For Zero Relief Cut.

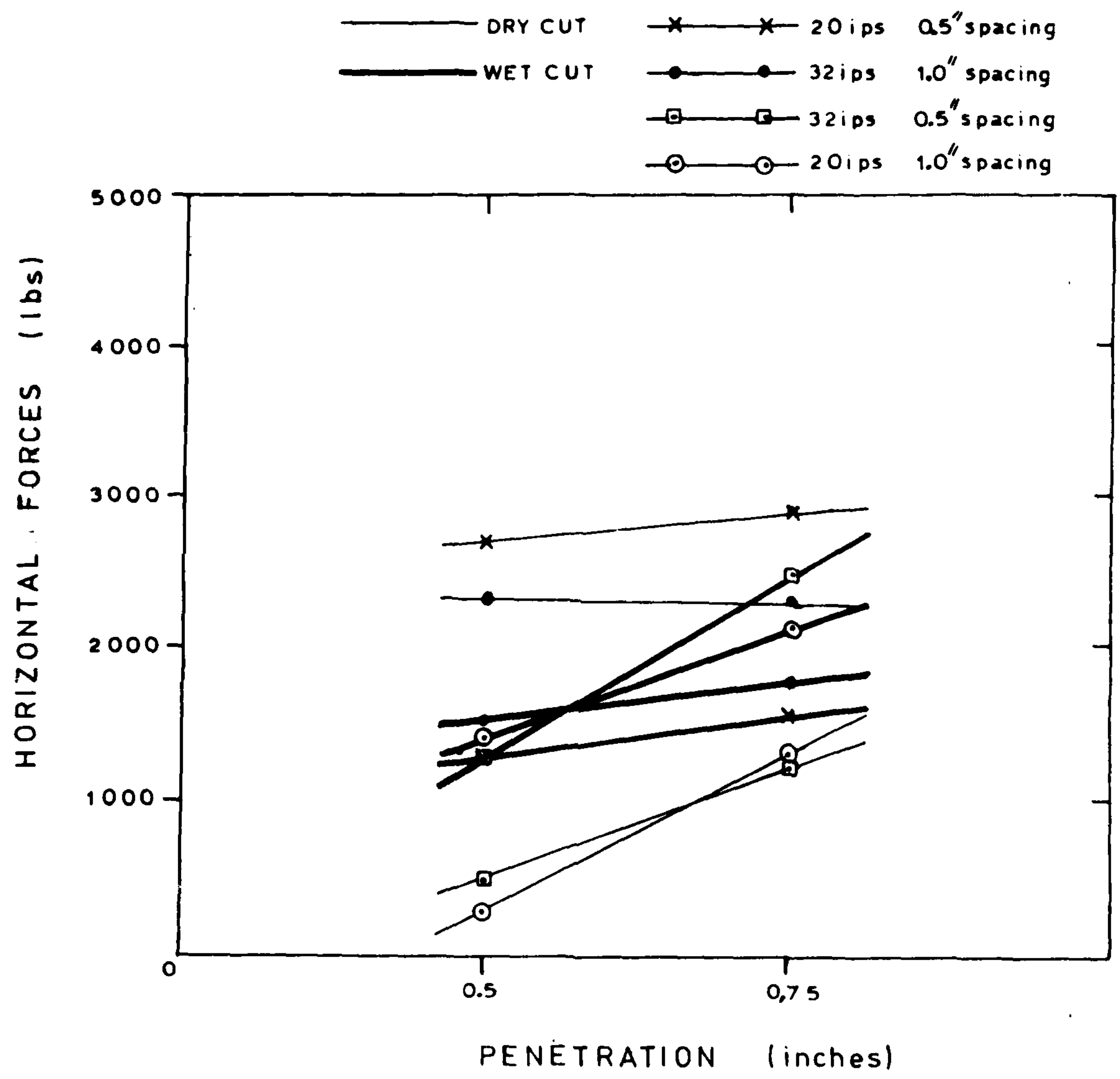


Figure C-25. Horizontal Forces vs. Penetration Depth For Zero Relief Cut.

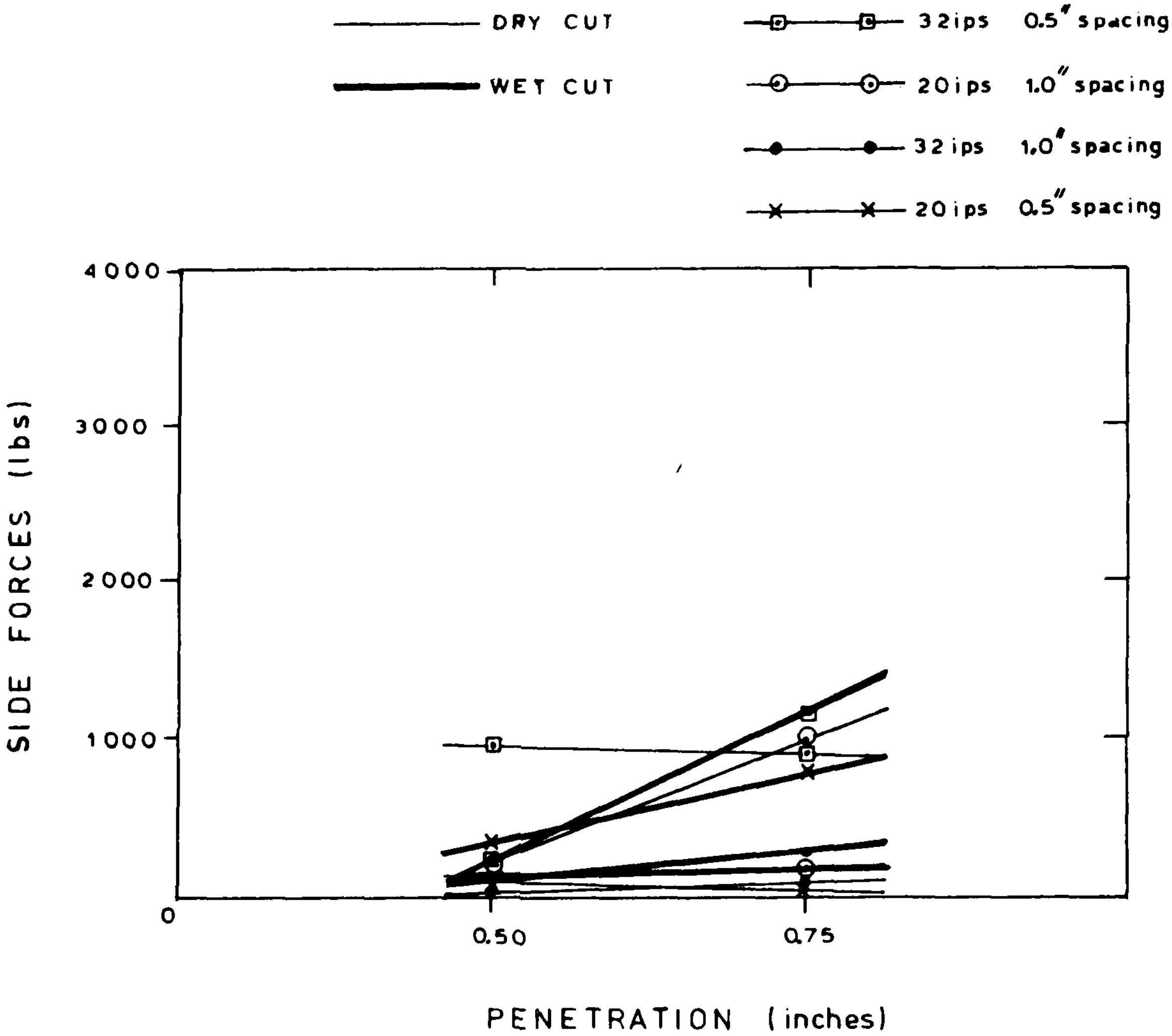


Figure C-26. Side Forces vs. Penetration Depth For Zero Relief Cut.

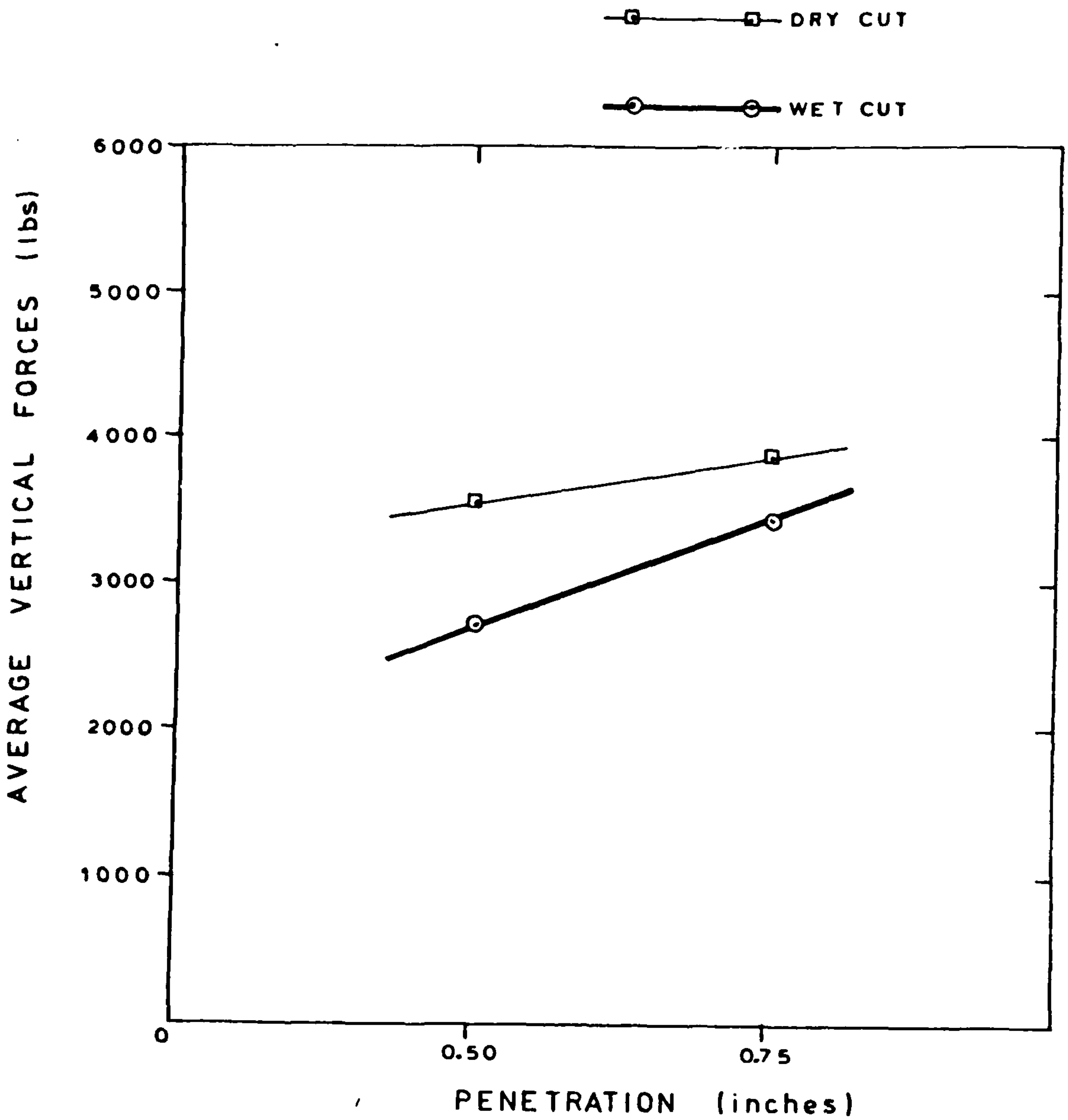


Figure C-27. Average Vertical Forces vs. Penetration Depth For Zero Relief Cut.

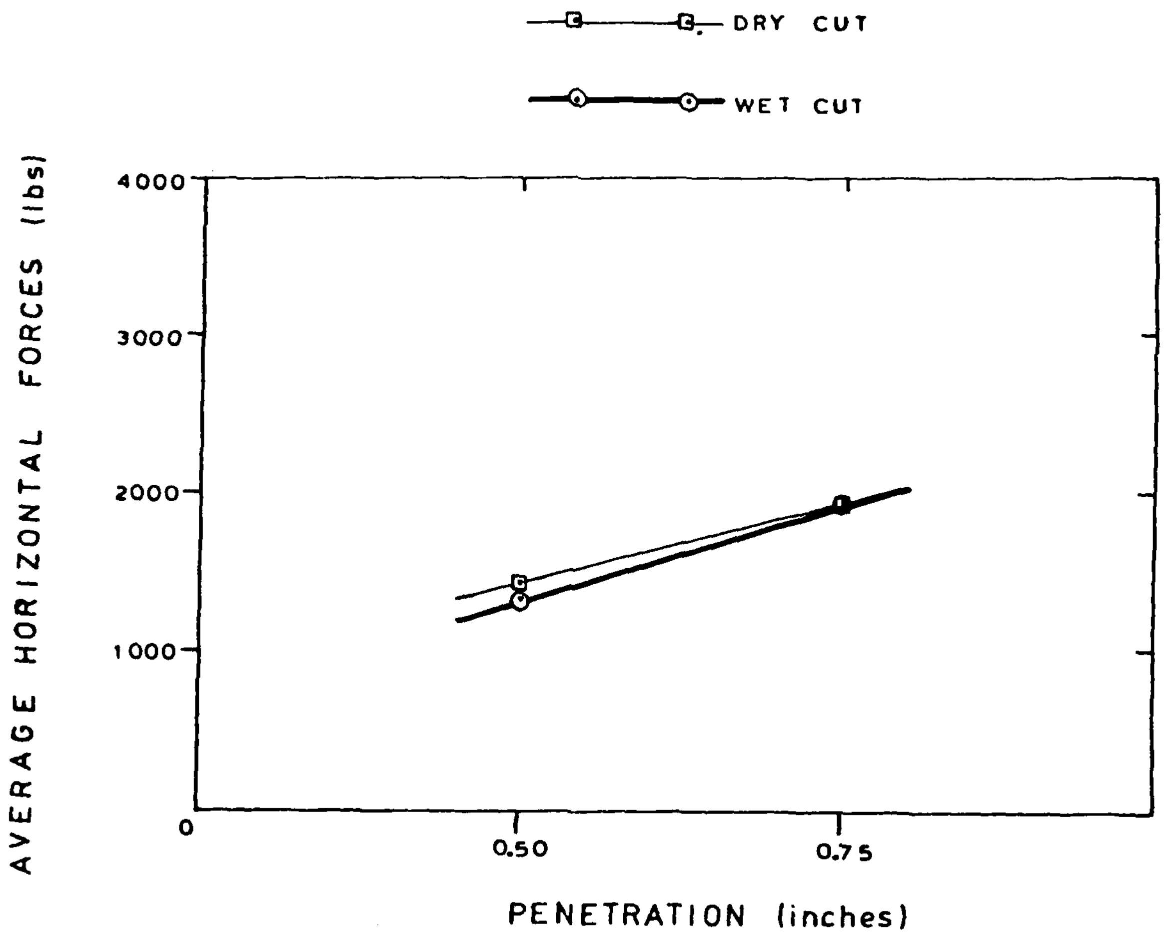


Figure C-28. Average Horizontal Forces vs. Penetration Depth For Zero Relief Cut.

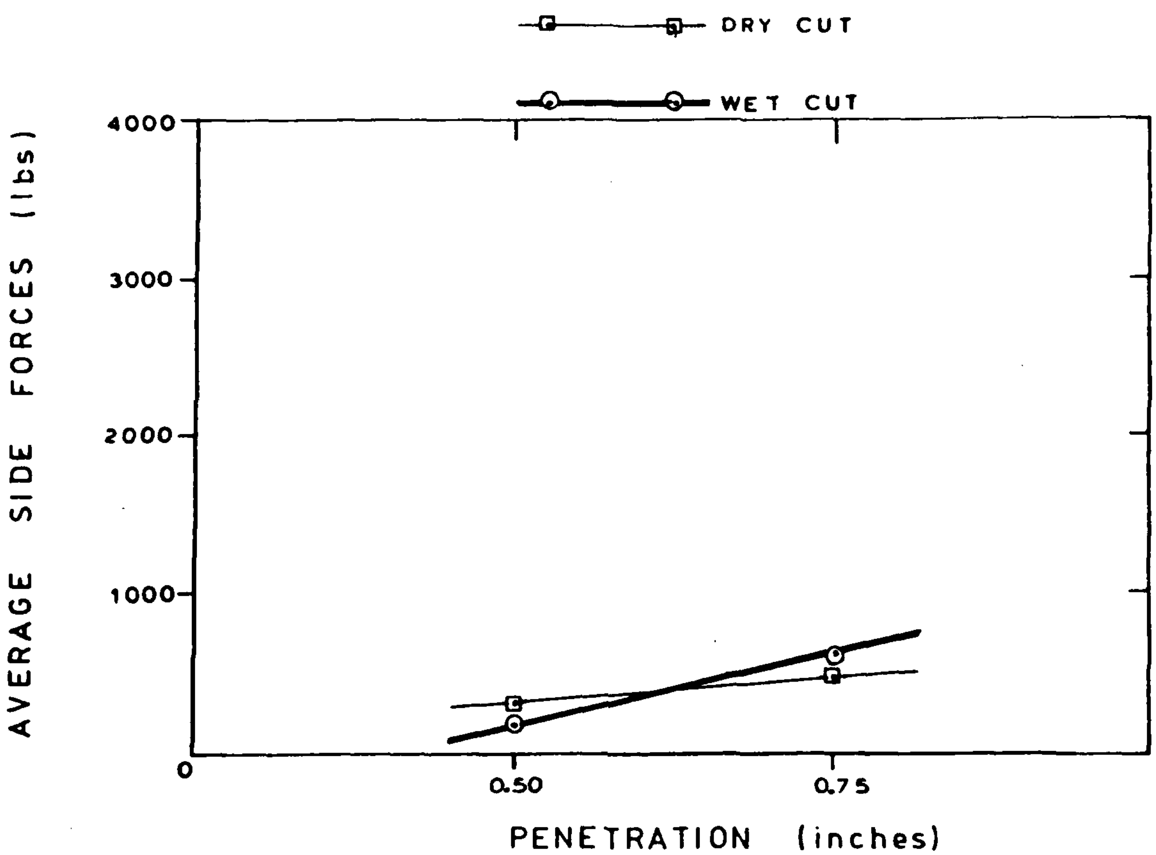


Figure C-29. Average Side Forces vs. Penetration Depth For Zero Relief Cut.

The reasons for this observation may be the small number of test data points as well as the cutting geometry which does not favor the waterjet action in propagating the microcracks.

d. Two-Side Relief Cut

The data points for dry cuts are limited, therefore, the comparison between the dry and wet cuts is not meaningful. However, from Figures C-16 and C-17, it can be concluded that two-side cuts have the smallest forces as compared to other cuts in both dry and wet cases.

e. Waterjet Kerfing Test

Waterjet kerfing tests were conducted with water pressure from 5,000 to 20,000 psi, nozzle sizes of 0.016 inch and 0.024 foot, and standoff distance of 1 to 3 inches. The test results are presented in Table C-4. The effectiveness of waterjet kerfing was only demonstrated at 20,000 psi at 15 ips with nozzle sizes of 0.016 and 0.024 inch to depths of 0.12 and 0.1 inch, respectively. This, in effect, indicates that concrete is difficult to kerf with waterjet at pressures of 20,000 psi or lower.

f. Comparison With Rock Cutting Data

The pick forces for waterjet-assisted cutting in Dakota sandstone and concrete are listed in Table C-5. The vertical forces measured for cutting concrete are larger than those measured for cutting Dakota sandstone, but the horizontal (cutting) forces for cutting concrete are less than half of those for sandstone. The horizontal force is the more critical force in the cutting process with respect to power requirements. This implies that concrete cutting is easier than sandstone cutting and the power required may be less than half of that for the sandstone. A design made by using sandstone data will definitely be on the conservative side for cutting concrete.

5. CONCEPTUAL DESIGN

Three basic conceptual concrete-cutting equipment designs that utilize the waterjet-assisted mechanical picks as cutting tools have been formulated. The first concept uses a cutting bar (Figure C-30) with picks mounted on a chain driven by a drive wheel. The second concept (Figure C-31) uses a ram cutter with picks mounted on the cutting edge of the ram. The ram cutter is driven by a nonconcentric arm and creates a cyclic motion in cutting the concrete. The third concept employs a circular wheel with picks mounted on the periphery. These three designs

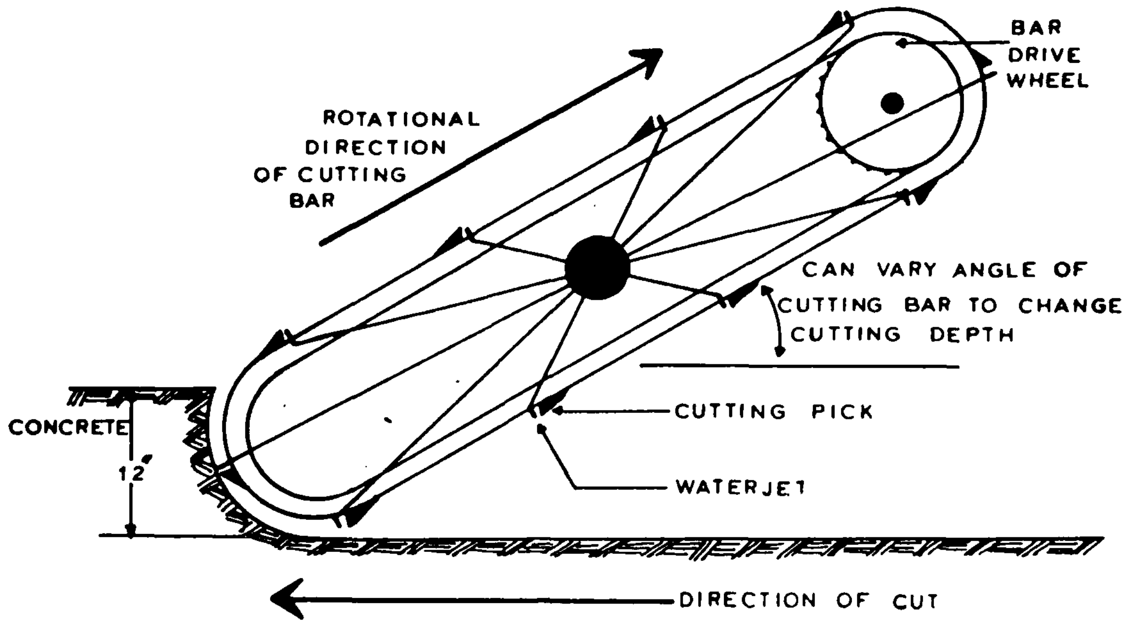
TABLE C-4. SUMMARY OF WATERJET KERFING TEST RESULTS.

Test No.	Pressure psi	Traverse ips	Standoff inch	Nozzle Size inch	Kerf	Remarks
1	5,000	15	1	0.016	0	cleaning action
2	10,000	15	1	0.016	0.005	
	"	30	1	"	0.025	
	"	45	1	"	0.008	
3	20,000	15	1	0.016	0.125	with spalling
	"	30	1	"	0.021	
	"	45	1	"	0.010	
4	20,000	15	3	0.016	0.013	
	"	30	3	"	0.005	
	"	45	3	"	0.0015	
5	5,000	15	3	0.024	0	
6	10,000	15	3	0.024	0.003	
	"	30	3	"	0.0015	
	"	45	3	"	0	
7	20,000	15	3	0.024	0.10	
	"	30	3	"	0.07	
	"	40	3	"	0.03	

TABLE C-5. COMPARISON OF CONCRETE AND SANDSTONE CUTTING FORCES.

	Cutting Depth inch	Vertical Force lbs	Cutting Force lbs
Dakota Sandstone	0.50	1,200	2,000
	0.75	900	1,800
Concrete	0.50	1,900	700
	0.75	1,750	600

SIDE VIEW OF THE CUTTING BAR



PLAN VIEW OF CUTTING BAR MACHINE

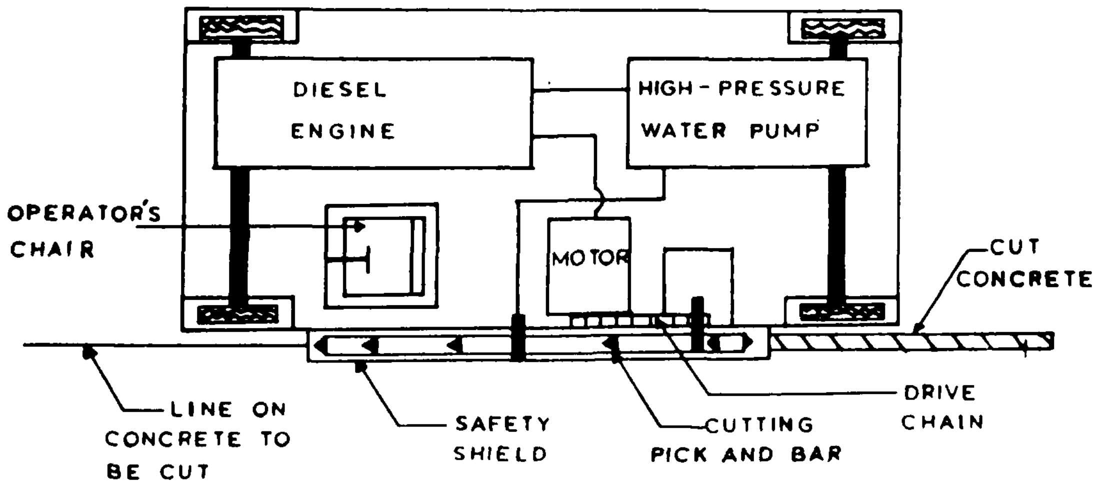
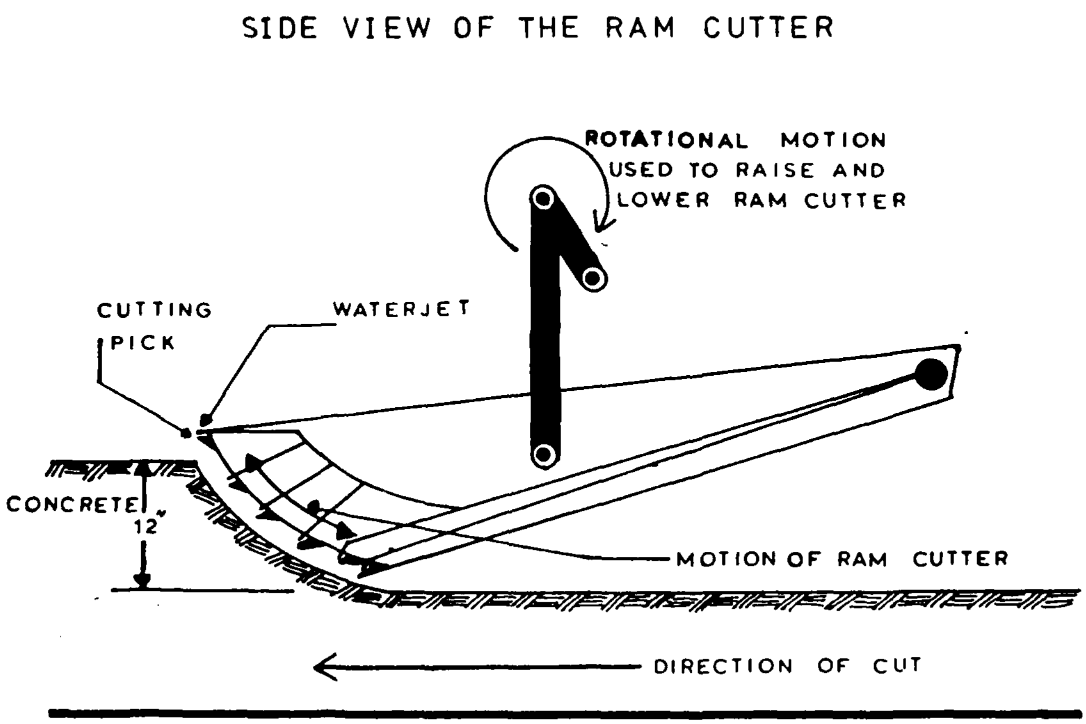


Figure C-30. Cutting Bar Prototype Concept.



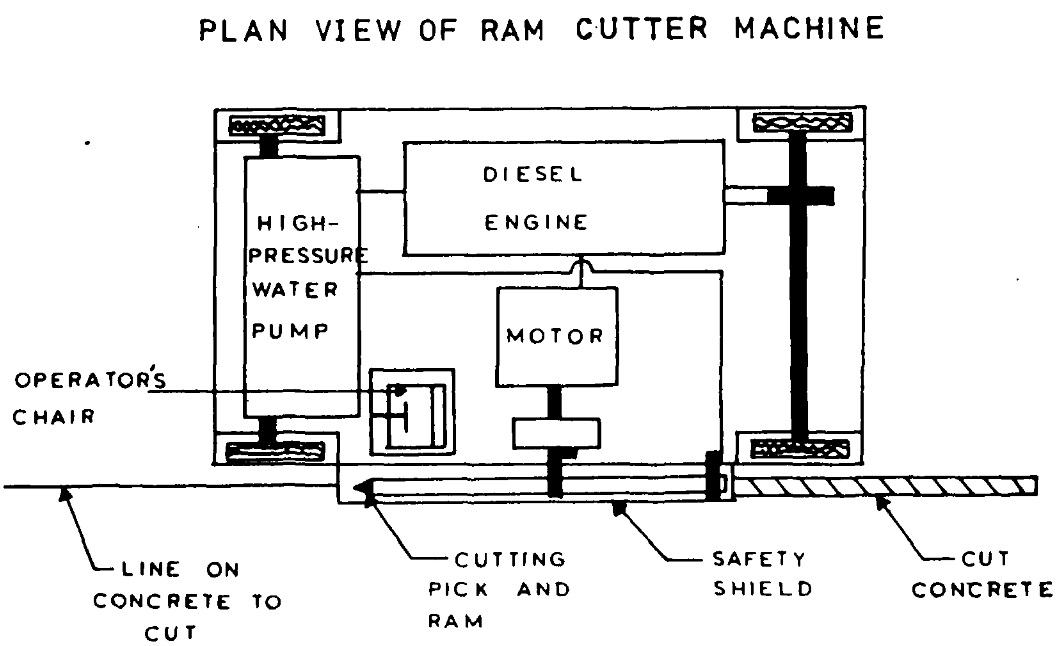


Figure C-31. Ram Cutter Protoytpe Concept.

all have their individual characteristics, advantages and disadvantages. These features are discussed further as follows:

a. Cutting Bar (Figure C-30)

(1) Advantages:

(a) Can cut to various depths.

(b) Large number of picks may be mounted on the long chain to reduce wear on each individual pick for a given amount of cutting.

(2) Disadvantages:

(a) The high-pressure water connection between the swivel and the pick has to change length, depending on the position of the pick which moves with the chain on the bar. This is a difficult feature to incorporate in practice.

(b) Large moment may develop due to the length of the cutting bar.

(c) The cutting structure may lack rigidity because of the length.

b. Ram Cutter

(1) Advantages:

(a) Cutting head design is simple.

(b) High-pressure water connection from the swivel to the nozzle is simple, and a swivel may not be needed.

(2) Disadvantages:

(a) The cyclic driving mechanism and cutting action create large cyclic forces. Large total power is required.

(b) Only small number of picks may be mounted from the limited surface on the cutting edge.

(c) Cuttings or debris may fall back into the slot.

c. The Cutting Wheel

(1) Advantages:

(a) Simple and stable geometry as well as driving mechanism.

(b) Large number of picks may be used.

(c) Uniform load on the cutting wheel from the picks.

(d) May achieve high cutting rate.

(2) Disadvantage:

(a) Need a High-Pressure Swivel. In weighing the advantages and disadvantages of the three concepts, the cutting wheel is selected for further design because it has the best characteristics for concrete cutting.

The general layout of the cutting wheel machine with its carrier is shown in Figure C-32. A diesel engine drives both the high-pressure water pump and a hydraulic motor which, in turn, drives the cutting wheel as well as the vehicle moving in the direction of the cut. The operator is located in the front of the machine on the cutting wheel side for ease of control and operation.

Assuming the depth of the cut per pick for each revolution is 0.5 inch, and there are 12 picks on the cutting wheel, the wheel will be able to cut 0.5 ft^2 per revolution. To have a cutting rate of 30 ft^2/minute, the wheel needs to rotate 60 rpm when the wheel cutting depth is 1 foot. At these cutting conditions, based on experimental data, the cutting force on each pick is 700 pounds. The power required for driving the cutting wheel is:

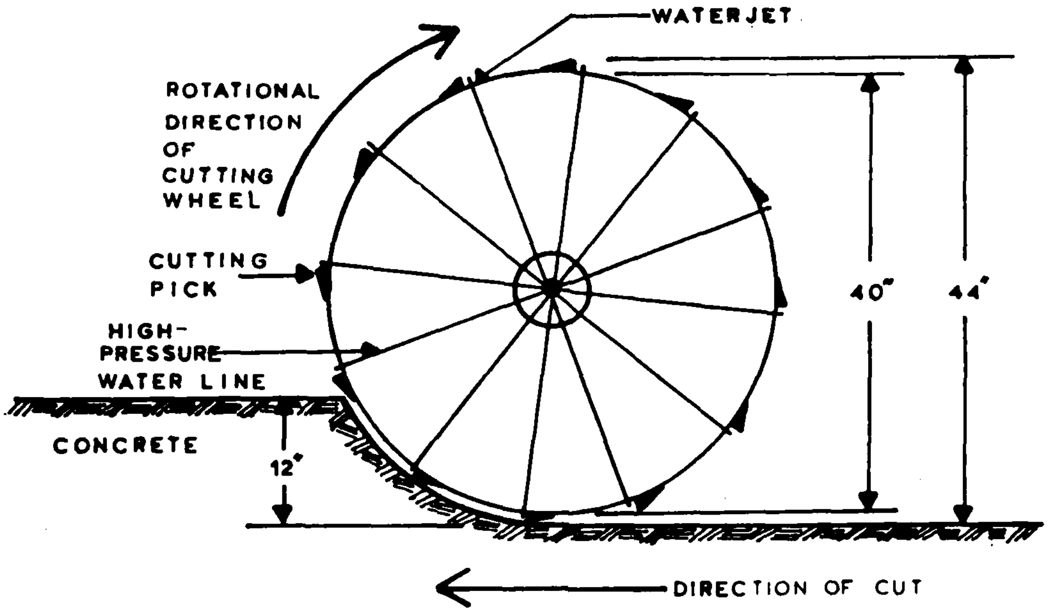
$$\text{Horsepower} = \frac{\text{(no. of picks)(force)(radius)(angular velocity)(drive requirement)}}{\text{(conversion factor)}}$$

$$= \frac{2 \times 700 \text{ lb} \times 1.8 \text{ ft} \times (2\pi \times 60 \text{ rpm})\ (1.5)}{33{,}000 \text{ ft-lb/min/hp}}$$

$$= 44 \text{ hp}$$

For design purposes, a very conservative estimate of the power requirement will be made here. If a factor of 1.5 is used for a margin of error, then the power required for the cutting wheel is approximately 70 horsepower. As a rough estimate, the power required to operate the carriage is taken as 30 horsepower. Approximately 10 horsepower are required to operate each high-pressure waterjet and with the use of a high-pressure swivel only six need operate at once. This means a total of

SIDE VIEW OF THE CUTTING WHEEL



PLAN VIEW OF CUTTING WHEEL MACHINE

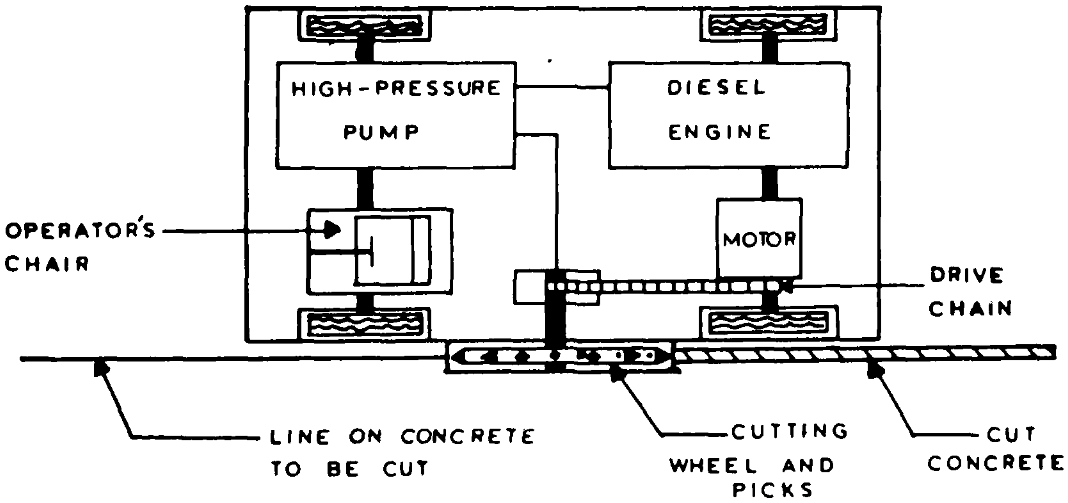


Figure C-32. Cutting Wheel Prototype Concept.

60 horsepower is needed for the jets, but again a design margin of 1.5 is used to give a requirement of 90 pump horsepower. Thus the total power requirement is estimated at 190 horsepower and the use of a 250-horsepower engine would supply an added 60 horsepower if needed. These estimates are summarized in Table C-6 and an estimate of the cost of system components is presented in Table C-7.

6. CONCLUSION AND RECOMMENDATION

From the concrete-cutting test data obtained, it is evident that the waterjet-assisted rock cutting technique is effective in concrete cutting. The cutting of concrete is very similar to cutting Dakota sandstone. A cutting design using sandstone data will always be on the conservative side.

A 30 ft^2/minute cutting rate may be achieved by using a circular cutting wheel of 44-inch diameter with a total power of 250 horsepower for operating both mechanical and waterjet apparatus on a cutting equipment.

It is recommended that a prototype be designed, constructed and field-tested to verify the waterjet-assisted concrete slotting technique.

TABLE C-6. SPECIFICATION OF FIELD TEST MACHINE.

Depth of cut:	0.5-inch pick
Number of picks:	12
RPM:	60
Cutting force /pick:	700 lbs
Picks in contact with concrete simultaneously:	2
Waterjet nozzle size:	0.025 in.
Waterjet pressure:	10,000 psi
Horsepower required / nozzle:	10 hp
Total waterjet horsepower:	90 hp
Total machine horsepower required:	100 hp
Total Design Machine horsepower:	250 hp

TABLE C-7. ESTIMATED CUTTING EQUIPMENT COST.

1.	Diesel engine: 250 hp	$20,000
2.	Waterjet pump: 100 hp, Triplex	$25,000
3.	Mechanical drive	$ 5,000
4.	Frame and cutting wheel	$ 8,000
5.	High-pressure swivel	$ 5,000
6.	Controls	$ 5,000
7.	Engineering design and fabrication	$25,000
		$93,000

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C-2 Wang, F. D. and Wolgamott, J. "Application of Water Jet-Assisted Pick Cutter for Rock Fragmentation," Fourth International Symposium on Jet Cutting Technology, Paper C1, BHRA, Fluid Eng., Crawfield, Bedford, England, April 1978.

C-3 Ropchan, D., Wang, F. D. and Wolgamott, J., Application of Water Jet-Assisted Drag Bit and Pick Cutter for the Cutting of Coal Measure Rocks, DOE/FE/0982-1, Final Technical Report, Prepared for the United States Department of Energy, Carbondale Mining Technology Center, Contract No. ET-77-G-01-9082.

C-4 Hood, M., "Cutting Strong Rock with a Drag Bit Assisted by High-Pressure Water Jets," Journal of the South African Institute of Mining and Metallurgy, November 1976.

C-5 Dubugnon, O., "An Experimental Study of Water Jet-Assisted Drag Bit Cutting of Rocks," Proceedings of the First U.S. Water Jet Conference, Golden, Colorado, April 1981.

C-6 Staff of the U.K. National Coal Board, "Seminar on Water Jet-Assisted Roadheader for Rock Excavation," DOE, May 26, 1982.

C-7 Bauman, L., "State of Investigations on High-Pressure Water Jet-Assisted Road Profile Cutting Technology," Proceedings of the First U.S. Water Jet Conference, Golden, Colorado, April 1981.

C-8 Kuzmich, I. A., Golden, Ju. A., Ruthberg, M. I., and Frolov, V. S., "A Combined Method for Rock Breakage," The Sixth International Symposium on Jet-Cutting Technology, BHRA, April 1982.

ANNEX 1 TO APPENDIX C

LINEAR CUTTING DATA

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 1
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	4	84	516	49	237
2	43	22	125	97	49
3	41	28	176	73	65
4	31	20	100	81	49
5	36	28	146	85	61
6	38	26	145	77	61
7	38	27	166	69	61
8	40	25	137	73	65
9	39	28	168	85	61
10	42	27	163	93	61
11	34	30	157	73	77
12	33	25	139	61	61
13	33	31	150	69	93
14	45	29	165	105	81
15	31	27	143	73	65
16	42	30	157	97	69
17	37	34	186	101	81

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	71	6397	2719	866	18050
2	760	1676	659	1715	3732
3	725	2132	928	1291	4950
4	548	1523	527	1432	3732
5	636	2132	769	1503	4646
6	672	1980	764	1361	4646
7	672	2056	875	1220	4646
8	707	1904	722	1291	4950
9	690	2132	885	1503	4646
10	743	2056	859	1644	4646
11	601	2285	827	1291	5864
12	583	1904	733	1078	4646
13	583	2361	791	1220	7083
14	796	2209	870	1856	6189
15	548	2056	754	1291	4930
16	743	2283	827	1715	5255
17	654	2589	980	1786	6169
AVG	671	2334	[illegible]	1415	5811
SD	40	269	119	66	817

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 2
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 32
CUT TIME (SEC): .64

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	34	14	61	97	41
2	22	17	89	81	65
3	20	13	71	85	53
4	22	17	90	97	65
5	26	20	99	89	73
6	28	17	95	81	53
7	29	19	102	97	85
8	17	17	86	77	57
9	21	17	81	69	61
10	29	20	93	105	65
11	28	17	97	97	81
12	27	21	108	81	81
13	22	16	79	93	59
14	25	18	102	109	65
15	34	16	101	101	77
16	45	21	138	117	65

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	939	1666	502	2680	4879
2	608	2023	733	2238	7735
3	553	1547	585	2348	6307
4	608	2023	741	2680	7735
5	718	2380	815	2459	8687
6	774	2023	782	2238	6307
7	801	2261	840	2680	10115
8	470	2023	708	2127	6783
9	580	2023	667	1906	7259
10	801	2380	766	2901	7735
11	774	2023	799	2680	9639
12	746	2499	889	2238	9639
13	608	1904	651	2569	8211
14	691	2142	840	3011	7735
15	939	1904	832	2790	9163
16	1243	2499	1136	3232	7735
AVG	741	2083	768	2549	7854
SD	48	70	36	90	360

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 3
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.75
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	1	80	540	45	173
2	33	18	105	69	53
3	63	26	161	121	65
4	71	27	202	141	49
5	61	27	228	121	85
6	64	30	233	113	57
7	68	33	243	125	69
8	58	30	216	113	65
9	56	29	234	105	53
10	55	30	210	105	57
11	48	26	195	113	65
12	47	24	185	101	65
13	58	30	249	101	65
14	42	23	181	105	49
15	41	23	177	113	57
16	55	26	206	81	61

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	18	6093	2893	796	13176
2	583	1371	553	1220	4036
3	1114	1980	848	2139	4950
4	1255	2056	1065	2493	3732
5	1078	2056	1202	2139	6474
6	1132	2285	1228	1998	4341
7	1202	2513	1281	2210	5255
8	1025	2285	1138	1998	4950
9	990	2209	1233	1856	4036
10	972	2285	1107	1856	4341
11	849	1980	1028	1998	4950
12	831	1828	975	1786	4950
13	1025	2285	1312	1786	4950
14	743	1752	954	1856	3732
15	725	1752	933	1998	4341
16	972	1980	1086	1432	4646
AVG	907	2294	1177	1848	5179
SD	77	271	127	105	577

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 4
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.75
BIT TRAVEL (IN): 20.0
BIT SPACING (IN) 0.5
CUTTING SPEED (IPS): 32
CUT TIME (SEC): .64

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	29	21	135	97	60
2	33	21	126	129	77
3	31	19	111	101	73
4	33	18	119	133	57
5	28	17	96	77	53
6	25	22	109	89	81
7	28	19	98	93	61
8	26	19	110	89	69
9	30	19	108	73	69
10	114	64	230	113	73
11	22	16	90	93	65
12	18	22	139	89	77
13	27	19	100	89	57
14	29	20	115	77	73
15	43	20	139	105	77
16	98	63	534	213	217

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	801	2499	1112	2680	7140
2	912	2499	1038	3564	9163
3	856	2261	914	2790	8687
4	912	2142	980	3674	6783
5	774	2023	791	2127	6307
6	691	2618	898	2459	9639
7	774	2261	807	2569	7259
8	718	2261	906	2459	8211
9	829	2261	889	2017	8211
10	3149	7616	1894	3122	8687
11	608	1904	741	2569	7735
12	497	2618	1145	2459	9163
13	746	2261	823	2459	6783
14	801	2380	947	2127	8687
15	1188	2380	1145	2901	9163
16	2707	7497	4397	5884	25823
AVG	1060	2968	1214	2866	9215
SD	193	465	229	240	1172

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 5
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 1.0
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	16	20	67	53	41
2	18	27	141	45	61
3	25	27	172	57	69
4	13	26	167	69	85
5	16	26	177	69	65
6	18	38	175	69	93
7	64	43	357	89	81

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	283	1523	353	937	3123
2	318	2056	743	796	4646
3	442	2056	906	1008	5255
4	230	1980	880	1220	6474
5	283	1980	933	1220	4950
6	318	2894	922	1220	7083
7	1132	3275	1881	1574	6169
AVG	429	2252	945	1139	5386
SD	129	248	188	103	541

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 6
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE

BIT PENETRATION	(IN):	0.5
BIT TRAVEL	(IN):	20.0
BIT SPACING	(IN):	1.0
CUTTING SPEED	(IPS):	32
CUT TIME	(SEC):	.64

SENSITIVITIES FOR THE LOAD CELL

SIDE CHANNEL	(LBS/MV):	26
VERTICAL CHANNEL	(LBS/MV):	112
DRAG CHANNEL	(LBS/MV):	7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	0	40	286	29	125
2	19	19	116	77	85
3	11	19	113	61	93
4	13	18	86	69	73
5	15	21	109	53	77
6	13	23	110	49	101
7	13	20	109	53	81
8	15	19	103	97	77

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	0	4760	2355	801	14875
2	525	2261	955	2127	10115
3	304	2261	930	1685	11067
4	359	2142	708	1906	8687
5	414	2499	898	1464	9163
6	359	2737	906	1354	019
7	359	2380	898	1464	9639
8	414	2261	848	2680	9163
AVG	342	2663	1062	1685	10591
SD	57	327	99	212	75

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 7
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE

BIT PENETRATION	(IN):	0.75
BIT TRAVEL	(IN):	20.0
BIT SPACING	(IN):	1.0
CUTTING SPEED	(IPS):	20
CUT TIME	(SEC):	1

SENSITIVITIES FOR THE LOAD CELL

SIDE CHANNEL	(LBS/MV):	26
VERTICAL CHANNEL	(LBS/MV):	112
DRAG CHANNEL	(LBS/MV):	7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	0	114	1666	0	221
2	50	38	230	109	81
3	49	35	267	113	77
4	0	0	0	41	193
5	2	30	227	69	85
6	13	16	109	45	65
7	60	42	352	101	113
8	4	17	102	17	101
9	10	16	74	45	49
10	6	63	440	37	169
11	5	23	99	1	113
12	13	20	109	69	57
13	50	26	218	93	65
14	36	33	267	97	85
15	54	33	271	129	77

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	0	8682	8780	0	16831
2	884	2894	1212	1927	6169
3	866	2666	1407	1998	5864
4	0	0	0	725	14699
5	35	2285	1196	1220	6474
6	230	1219	574	796	4950
7	1061	3199	1855	1786	8606
8	71	1295	538	301	7692
9	177	1219	390	796	3732
10	106	4798	2319	654	12871
11	88	1752	522	18	8606
12	230	1523	574	1220	4341
13	884	1980	1149	1644	4950
14	636	2513	1407	1715	6474
15	955	2513	1428	2281	5864
AVG	415	2569	1557	1139	7875
SD	109	538	558	196	1046

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 8
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.75
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 1.0
CUTTING SPEED (IPS): 32
CUT TIME (SEC): .64

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	2	34	258	45	113
2	38	20	151	121	85
3	7	36	268	77	133
4	1	20	124	67	85
5	3	9	68	57	85
6	11	36	267	57	133
7	1	14	95	9	77
8	7	10	54	21	57
9	12	33	227	69	133
10	1	17	85	5	73
11	4	14	65	25	49
12	28	21	132	121	93
13	40	26	190	113	69
14	177	108	704	285	269

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	55	4046	2124	1243	13447
2	1050	2380	1243	3343	10115
3	193	4284	2207	2127	15827
4	28	2380	1021	1851	10115
5	83	1071	560	1575	10115
6	304	4284	2199	1575	15827
7	28	1666	782	249	9163
8	193	1190	445	580	6783
9	332	3927	1869	1906	15827
10	28	2023	700	138	8687
11	111	1666	535	691	5831
12	774	2499	1087	3343	11067
13	1105	3094	1565	3122	8211
14	4890	12852	5797	7873	32011
AVG	655	3383	1581	2115	12359
SD	353	816	380	546	1811

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 9
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

ORIFICE SIZE (IN): 0.025
PRESSURE (PSI): 10000

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	0	94	720	0	209
2	28	24	133	89	49
3	38	26	173	97	73
4	15	32	224	73	89
5	4	19	56	86	29
6	6	25	33	74	65
7	24	32	[illegible]	73	97
8	6	13	[illegible]	45	45
9	9	17	38	43	25
10	23	32	256	89	73
11	4	17	50	61	41
12	9	16	29	63	21
13	30	19	152	93	45

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	0	7159	3794	0	15917	GAUGE CUT
2	495	1828	701	1574	3732	
3	672	1980	912	1715	5560	
6	265	2437	1180	1291	6779	
5	71	1447	295	1520	2209	
4	106	1904	174	1308	4950	
9	424	2437	1449	1291	7388	
8	106	990	295	796	3427	
7	159	1295	200	760	1904	
12	407	2437	1349	1574	5560	
11	71	1295	264	1078	3123	
10	159	1219	153	1114	1599	
13	530	1447	801	1644	3427	GAUGE CUT
AVG	267	2144	890	1205	5944	
SD	61	457	285	136	1079	
AVG	365	2437	1326	1385	6575	AVERAGE OF
SD	87	0	136	163	933	6,9,12
AVG	283	1508	493	1332	3619	AVERAGE OF
SD	282	401	296	385	1230	2,3,5,8,11
AVG	141	1473	176	1061	2818	AVERAGE OF
SD	31	375	24	278	1853	4,7,10

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 10
BIT TYPE: CONICAL PICK — ORIFICE SIZE (IN): 0.025
ROCK TYPE: CONCRETE — PRESSURE (PSI): 10000
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 32
CUT TIME (SEC): .64

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	26	12	68	93	65
2	[illegible]	11	93	89	41
3	[illegible]	[illegible]	106	86	69
4	[illegible]	[illegible]	[illegible]	57	101
5	[illegible]	18	[illegible]	43	45
6	1	17	26	5	33
7	11	26	168	61	109
8	1	17	35	65	45
9	1	13	14	67	17
10	15	27	198	73	101
11	1	17	33	86	41
12	16	15	15	36	49

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	718	1428	725	2569	7735	GAUGE CUT
2	829	1309	766	2459	4879	
3	580	1904	865	2308	8211	
6	221	2618	1268	1022	12019	
5	249	2142	207	1188	5355	
4	28	2023	214	138	3927	
9	304	3094	1383	1685	12971	
8	28	2023	288	1796	5355	
7	28	1547	115	1851	2023	
12	414	3213	1630	2017	12019	GAUGE CUT
11	28	2023	[illegible]	2376	4879	
10	226	1785	124	967	5831	
AVG	309	2092	658	1701	7100	
SD	97	182	160	223	1067	
AVG	263	2856	1326	1354	12495	AVERAGE OF
SD	59	337	81	469	673	6,9
AVG	343	1880	480	2033	5736	AVERAGE OF
SD	243	330	302	541	1404	2,3,5,8,11
AVG	111	1785	151	985	3927	AVERAGE OF
SD	143	238	55	857	1904	4,7,10

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 11
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.75
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 0.5
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

ORIFICE SIZE (IN): 0.025
PRESSURE (PSI): 10000

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 26
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	41	113	627	98	253
2	33	15	115	97	53
3	36	32	256	109	121
4	5	13	25	43	43
5	5	21	20	71	43
6	39	34	302	141	93
7	11	20	42	91	49
8	14	16	29	9	37
9	52	35	336	121	89
10	16	19	15	81	35
11	17	25	8	74	25
12	54	18	206	141	77

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	[illegible]	8606	3704	1733	15268	GAUGE CUT
2	583	[illegible]	606	1715	4076	
5	636	2437	1349	1927	9915	
4	88	990	132	760	3275	
3	88	1599	105	1255	3275	
8	690	2580	1592	2493	7083	
7	194	1623	221	1609	3732	
6	248	1319	153	159	2818	
11	[illegible]	2666	1721	[illegible]	6228	
10	287	1447	74	1432	2666	
9	301	1904	42	1308	1904	
12	955	1371	1086	2493	5866	GAUGE CUT
AVG	474	2291	826	1585	5826	
SD	93	623	301	263	1436	
AVG	703	2564	1521	2180	[illegible]	AVERAGE [illegible]
SD	141	117	212	280	[illegible]	[illegible]
AVG	287	1276	260	1379	[illegible]	AVERAGE [illegible]
SD	213	252	278	429	[illegible]	[illegible]
AVG	212	1529	100	907	[illegible]	AVERAGE [illegible]
SD	111	743	56	649	[illegible]	[illegible]

LINEAR CUTTING TEST [illegible]

TEST NUMBER: [illegible]
BIT TYPE: [illegible]
ROCK TYPE: [illegible]
BIT PENETRATION (IN): [illegible]
BIT TRAVEL (IN): [illegible]
BIT SPACING (IN): [illegible]
CUTTING SPEED (IPS): [illegible]
CUT TIME (SEC): [illegible]

[illegible] SIZE (IN): 0.025
PRESSURE (PSI): 10000

SENSITIVITIES FOR THE [illegible]
SIDE CHANNEL [illegible] (MV): [illegible]
VERTICAL CHANNEL [illegible] (MV): [illegible]
DRAG CHANNEL [illegible] (MV): [illegible].75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
[illegible]		18	[illegible]	1[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1[illegible]7	11[illegible]	[illegible]
3	[illegible]	[illegible]	[illegible]	115	181
4	[illegible]	1[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	71	81
6	[illegible]	57	[illegible]	133	11[illegible]
[illegible]	15	17	[illegible]	11[illegible]	[illegible]
8	1[illegible]	12	1[illegible]	[illegible]	33
9	30	51	[illegible]	[illegible]	97
10	[illegible]	[illegible]	1[illegible]	[illegible]	[illegible]
11	[illegible]	16	13	1[illegible]	[illegible]

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	[illegible]	[illegible]	11[illegible]	[illegible]	[illegible]	GAUGE CUT
[illegible]	1[illegible]	[illegible]	158[illegible]	31[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1[illegible]	
4	[illegible]	1[illegible]	1[illegible]	1[illegible]	[illegible]	
5	[illegible]	17[illegible]	[illegible]	1[illegible]	[illegible]	
8	1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	414	1[illegible]	[illegible]	30[illegible]	[illegible]	
[illegible]	420	1428	[illegible]	[illegible]	[illegible]	
11	10[illegible]	3689	314	[illegible]	11[illegible]	GAUGE CUT
10	[illegible]	2023	1[illegible]	2[illegible]	[illegible]499	
[illegible]	[illegible]	1[illegible]	1[illegible]	[illegible]	[illegible]	
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AVERAGE OF
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible],8
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AVERAGE OF
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible],4,7,11
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AVERAGE OF
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible],[illegible],9

LINEAR CUTTING TEST JULY, 1982

TEST NUMBER: 13
BIT TYPE: CONICAL PICK
ROCK TYPE: CONCRETE
BIT PENETRATION (IN): 0.5
BIT TRAVEL (IN): 20.0
BIT SPACING (IN): 1.0
CUTTING SPEED (IPS): 20
CUT TIME (SEC): 1

ORIFICE SIZE (IN): 0.025
PRESSURE (PSI): 10000

SENSITIVITIES FOR THE LOAD CELL
SIDE CHANNEL (LBS/MV): 76
VERTICAL CHANNEL (LBS/MV): 112
DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	4	42	264	41	97
2	24	31	170	61	65
3	6	4	300	[illegible]	106
4	2	28	163	1	89
5	6	21	110	[illegible]	[illegible]
6	7	42	265	25	[illegible]
7	2	18	133	13	[illegible]
8	6	13	81	[illegible]	[illegible]
9	9	44	288	33	[illegible]
10	3	28	[illegible]	[illegible]	[illegible]
11	6	15	[illegible]	[illegible]	[illegible]
12	10	[illegible]	[illegible]	[illegible]	[illegible]
13	17	21	130	51	89
14	14	15	82	49	63

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	71	3199	1591	725	7388	GAUGE CUT
2	474	2361	896	1078	4950	
5	106	305	1581	513	7992	
4	35	2137	859	18	6778	
3	106	1599	580	301	4646	
8	124	3199	1397	442	9825	
7	35	1371	701	230	6474	
6	106	990	427	442	[illegible]	
11	159	3351	169	583	[illegible]	
10	53	132	443	442	7692	
9	166	1142	[illegible]	583	[illegible]	
13	127	2209	101	932	[illegible]	
14	301	1599	[illegible]	1078	[illegible]	[illegible]
12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
AVG	147	[illegible]	[illegible]	[illegible]	[illegible]	
SD	30	[illegible]	111	[illegible]	[illegible]	
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SD	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SD	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SD	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] NEAR CUTTING T[illegible] - [illegible]

TEST NUMBER [illegible] 14
BIT TYPE [illegible]
ROCK TYPE [illegible] CONCRETE
BIT PENETRATION (IN) [illegible]
BIT TRAVEL (IN) 20.[illegible]
BIT SPACING (IN) [illegible]
CUTTING SPEED ([illegible]) [illegible]
CUT TIME ([illegible]) [illegible]

[illegible] (IN) [illegible] 0.03[illegible]
[illegible] ([illegible]) 30[illegible]

SENSITIVITIES F[illegible]
SIDE CHANNEL [illegible] [illegible]
VERTICAL CHANNEL [illegible] [illegible]
DRAG CHANNEL [illegible] [illegible]

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	89	[illegible]
3	[illegible]	[illegible]	1[illegible]	[illegible]	11[illegible]
4	[illegible]	[illegible]	118	[illegible]	1[illegible]1
5	[illegible]	1[illegible]	[illegible]3	29	[illegible]3
6	[illegible]	[illegible]3	[illegible]	[illegible]	109
7	3	20	1[illegible]	89	77
8	[illegible]	19	[illegible]	13	57
9	[illegible]	30	1[illegible]	[illegible]	101
10	2	[illegible]	[illegible]	[illegible]	69
11	6	12	[illegible]56	11	89
12	5	22	20[illegible]	49	1[illegible]3
13	[illegible]	20	136	[illegible]	[illegible]7
14	5	[illegible]	[illegible]	17	[illegible]
15	7	[illegible]	1[illegible]	4[illegible]	[illegible]3
16	1	2[illegible]	1[illegible]	[illegible]	89
17	[illegible]	10	[illegible]	43	65

RESULTS ([illegible])

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	[illegible]	5871	[illegible]038	[illegible]28	2011[illegible]	GAUGE CUT
[illegible]	[illegible]3	1906	[illegible]	[illegible]	8687	
[illegible]	83	3451	1[illegible]	[illegible]	13[illegible]3	
[illegible]	[illegible]	[illegible]380	[illegible]	[illegible]	1[illegible]	
[illegible]	1[illegible]	1928	[illegible]	801	[illegible]	
8	[illegible]	[illegible]	11[illegible]	1[illegible]	1[illegible]1	
[illegible]	83	[illegible]60	10[illegible]	[illegible]	[illegible]3	
[illegible]	[illegible]78	11[illegible]	[illegible]	[illegible]	6[illegible]	
[illegible]	166	3[illegible]	[illegible]	[illegible]	1201[illegible]	
1[illegible]	[illegible]5	2023	[illegible]	[illegible]	9[illegible]11	
[illegible]	166	16[illegible]8	[illegible]	[illegible]	10591	
1[illegible]	[illegible]	3213	1[illegible]	1354	1344[illegible]	
[illegible]3	[illegible]	3380	11[illegible]	[illegible]	11[illegible]3	
[illegible]	138	952	[illegible]	[illegible]70	[illegible]	
[illegible]	1[illegible]3	[illegible]	[illegible]	1203	11067	GAUGE CUT
1[illegible]	[illegible]	[illegible]609	1038	178	10691	
15	[illegible]3	11[illegible]	[illegible]	912	7735	
AVG	[illegible]	[illegible]3	1[illegible]	977	10899	
SD	[illegible]	[illegible]	[illegible]	1[illegible]	[illegible]	
AVG	[illegible]	[illegible]3	1058	[illegible]		
SD	[illegible]	[illegible]	1[illegible]	[illegible]		
AVG	[illegible]	[illegible]1	[illegible]	[illegible]7		
SD	[illegible]	[illegible]	[illegible]	[illegible]		
AVG	[illegible]	1[illegible]	[illegible]	[illegible]		
SD	[illegible]	109	[illegible]	[illegible]		

LINEAR CUTTING TEST - JULY, 1982

TEST NUMBER: 15

BIT TYPE: CONICAL PICK — ORIFICE SIZE (IN): 0.035

ROCK TYPE: CONCRETE — PRESSURE (PSI): 3000

BIT PENETRATION (IN): 0.25

BIT TRAVEL (IN): 20.0

BIT SPACING (IN): 1.0

CUTTING SPEED (IPS): 20

CUT TIME (SEC): 1

SENSITIVITIES FOR THE LOAD CELL

SIDE CHANNEL (LBS/MV): 26

VERTICAL CHANNEL (LBS/MV): 112

DRAG CHANNEL (LBS/MV): 7.75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	2	61	497	69	165
2	37	27	203	69	61
3	6	55	414	53	145
4	[illegible]	27	169	1	85
5	5	20	102	17	81
6	8	47	387	25	137
7	2	23	161	1	77
8	11	12	62	61	45
9	13	51	442	57	149
10	1	24	153	1	77
11	7	16	102	33	65
12	11	43	409	45	129
13	0	20	159	1	97
14	7	10	88	21	57
15	37	28	219	81	[illegible]

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
1	35	4646	2619	1220	12566	GAUGE CUT
2	654	2056	107	1220	4646	
5	106	4189	[illegible]	937	11043	
4	35	2056	[illegible]	18	6474	
3	88	1523	538	301	6169	
8	141	3580	2039	442	10434	
7	35	1752	848	18	5864	
6	194	914	327	1078	3427	
11	230	3884	2329	1008	11348	
12	19	1828	806	18	5864	
9	[illegible]	1219	539	583	4050	
14	194	3275	2155	706	[illegible]	
13	[illegible]	[illegible]	938	18	7788	
10	[illegible]	[illegible]	[illegible]	[illegible]	4036	
15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	GAUGE CUT
AVG	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
SD	[illegible]	[illegible]	[illegible]	173	201	
AVG	[illegible]	[illegible]	[illegible]	706	[illegible]	AVERAGE OF
SD	[illegible]	[illegible]	[illegible]	[illegible]	675	5,8,11,14
AVG	[illegible]	[illegible]	[illegible]	[illegible]	6047	AVERAGE OF
SD	[illegible]	[illegible]	105	538	1001	2,4,7,10,13
AVG	[illegible]	[illegible]	[illegible]	583	[illegible]	AVERAGE OF
SD	[illegible]	[illegible]	[illegible]	[illegible]	1177	3,6,9,12

LINEAR CUTTING TEST [illegible] 198[illegible]

TEST NUMBER: [illegible]
BIT TYPE: [illegible] PICK
ROCK TYPE: [illegible]
BIT PENETRATION (IN) [illegible]
BIT TRAVEL (IN) [illegible]
BIT SPACING (IN) [illegible]
CUTTING SPEED (IPS) 32
CUT TIME (SEC) .64

[illegible] (IN) 0.035
[illegible] (PSI) 3000

SENSITIVITIES FOR [illegible]
SIDE CHANNEL (LBS/MV) [illegible]
VERTICAL CHANNEL (LBS/MV) 11.[illegible]
DRAG CHANNEL (LBS/MV) [illegible].75

INPUT

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE
1	[illegible]	37	320	21	141
2	28	[illegible]	140	[illegible]	89
3	8	[illegible]	[illegible]	53	121
4	[illegible]	12	[illegible]	1	61
5	[illegible]	9	[illegible]	69	[illegible]
6	14	[illegible]	[illegible]	[illegible]	[illegible]
7	1	16	[illegible]	[illegible]	[illegible]
8	[illegible]	9	[illegible]	[illegible]	[illegible]
9	[illegible]	25	[illegible]	69	[illegible]
10	1	[illegible]	114	[illegible]	81
11	[illegible]	11	[illegible]	41	61
12	[illegible]	[illegible]	[illegible]	[illegible]	117
13	[illegible]	[illegible]	[illegible]	1	41
14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

RESULTS (LBS)

CUT NUMBER	SIDE FORCE	VERT FORCE	DRAG FORCE	SIDE PEAK FORCE	VERT PEAK FORCE	
[illegible]	[illegible]	4403	[illegible]	[illegible]	[illegible]	GAUGE CUT
[illegible]	[illegible]	2618	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	3651	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	1428	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	1071	[illegible]	1906	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	840	[illegible]	[illegible]	
[illegible]	[illegible]	1071	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	1668	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	801	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	1333	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	GAUGE CUT
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
AVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
AVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AVERAGE [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AVERAGE [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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AD-A131 771 RAPID RUNWAY REPAIR PROGRAM SUBTASK 107 - RAPID CONCRETE CUTTING(U) BDM CORP MCLEAN VA R K MOATS ET AL. JUN 83 BDM/W-82-770-TR AFESC/ESL-TR-83-09 F08635-80-C-0206 3/3

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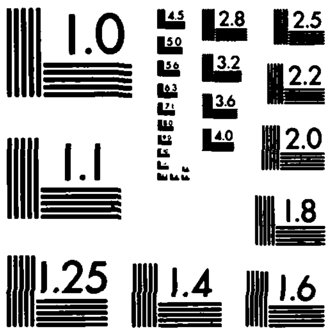

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ANNEX 2 TO APPENDIX C

WATERJET KERFING REPORT

ANNEX 2 TO APPENDIX C

WATERJET KERFING REPORT

The material in this annex was prepared for Engineering and Science Technology, Inc. by Dr. A. David Summers at the University of Missouri-Rolla, Rolla, Missouri.

1. INTRODUCTION

This is a report on testing two blocks of concrete, supplied to the University of Missouri-Rolla, by Dr. Fun-Den Wang and tested under the following conditions. Two nozzles were tested, of 0.016-inch diameter and 0.024-inch diameter, jet pressures of 5,000, 10,000, 20,000 psi were used, and the lathe was rotated at 74 rpm, giving jet traverse speeds which varied from 15 inches per second to 45 inches per second.

The concrete samples were placed in the chuck of the lathe and rotated while the waterjet nozzle was clamped in the horizontal feed of the lathe. As the concrete made a revolution the waterjet cut a slight spiral, with the feed between successive passes of 0.178 inch. In large measure, this removed interference between successive passes except for those cases where the waterjet was impinging large particles of aggregate. This allowed analysis of the effect of traverse speed over the required range of velocity.

The depths measured in the concrete are as follows:

Run 1: 0.016-inch nozzle at 5,000 psi, at a standoff distance of 1 inch. At 15 ips the jet was cutting only approximately 0.0015 inch into the concrete. This is mainly just a very thin grooving of the surface cement with no overall penetration but a cleaning action on the concrete by the time the jet has reached the 40 ips range.

Run 2: 0.016-inch nozzle at 10,000 psi. At 15 ips the jet was cutting to a depth of 0.005 inch; at 30 ips this had been reduced to 0.0025 inch, and by 45 ips the depth had been reduced to 0.001 inch. Occasional chipping had occurred, at which point depths up to 0.008 inch were achieved, but this was very small.

Run 3: Using a 0.016-inch nozzle, at 20,000 psi, a maximum penetration of 1/8 inch at 15 ips was achieved with spalling of the aggregate and removal of the intervening ribs at the slower speed. At 30 ips, the jet was only cutting an average of 0.021 inch although, at points where spalling occurred, up to 0.1 inch depths were achieved. At 45 ips, the jet was only cutting 0.01 inch deep.

This test was repeated, but with the jet located some 3 inches from the target surface, again running the .016 inch nozzle. At 20,000 psi, the

results were that at 15 ips, the jet penetrated 0.013 inch; at 30 ips, 0.005 inch, and at 45 ips, 0.0015 inch.

The first block was then removed and the second block placed in the lathe chuck. The following three tests were then carried out with the 0.024 inch diameter jet. Run 5 was carried out at 5,000 psi; no measurable penetration of the sample could be monitored. The path of the jet over the surface could be distinquished by the fact that the waterjet was cleaning out the pores of the cement.

Raising the pressure to 10,000 psi for Run 6, at 15 ips, the jet was cutting approximately 0.003 inch; at 30 ips, 0.0015 inch, and at 45 ips there was no detectable penetration.

The jet was raised to 20,000 psi, again with the 0.024-inch nozzle diameter, for a test run. In Run 7, at 15 ips, there was considerable spalling around the jet passage and a depth of slot of approximately 0.1 inch was achieved. At 30 ips this had been reduced to 0.07 inch and at 40 ips the jet was cutting approximately only 0.03 inch into the cement.

2. COMMENT

These jet passes were made at relatively high linear traverse velocities with a relatively small jet. To facilitate the program, the nozzle was held stationary and the sample was moved. Were the reverse to be the case, then previous experimentation has indicated that the results achieved would be even less in magnitude than those currently obtained. These results indicate that it is only at approximately 20,000 psi that waterjets of this size can be anticipated to do any satisfactory cutting of the concrete. Such a conclusion would be erroneous if considered outside of the test frame parameters of this particular series.

To understand what is meant, it is necessary to consider several different facets of the way in which waterjets cut concrete and other rocks. The waterjet takes a certain finite amount of time to penetrate into the rock. The jet is moving at approximately 1,200 fps at a pressure of 10,000 psi. At that pressure the water will take approximately 10 ms to achieve maximum penetration. If one accepts a nozzle diameter of 0.016 inch, where the jet has a zone of influence of approximately 3 times its diameter, this means that the jet will be influencing approximately 0.048 inch of the target surface at one time. Thus, a maximum traverse velocity to achieve full penetration might be considered to be where the jet was resident on this distance for a period of 10 ms. This would give a maximum traverse velocity of some 4.8 ips, which is considerably slower than the traverse velocities of this test. Further, the waterjet penetrates material by a process of crack growth, extending the crack by pressurizing fluid within the existing aperture.

With a relatively high traverse velocity and low penetration of the sample there is very little opportunity for the water to penetrate into

cracks and for there to be sufficient water behind the fluid front to provide adequate pressurization for effective crack growth. Thus, the results of this particular test are more indicative of the peculiar test conditions pertaining thereto.

Much more effective penetration could be achieved if the jet were operated at a higher flow volume or if the jet traverse velocity were decreased. This is validated by the fact that at 10,000 psi with a relatively slow traverse speed, on the order of 2 to 3 ips, but at a higher flow (approximately .06-inch diameter nozzle), the waterjet can cut through 6 inches of concrete. The reason for the difference lies in allowing the waterjet to fully exploit any cracks within the vicinity of the impact point, and to have enough energy resident in the jet at that point for a sufficient time to remove the material.

The use of a larger nozzle diameter has been beneficial in two ways. First, the larger impact area makes it more likely that flaws will be exploited by the waterjet action. Second, that if a larger amount of energy is transferred from the nozzle to the target surface, without reduction, more energy will thus be available to pressurize any cracks encountered.

It has been generally observed that once the threshold pressure required for cutting a material is exceeded, a more effective increase in cutting performance is achieved at higher power levels by an increase in flow rate rather than by an increase in pressure. However, for the small diameter nozzles used in these tests it has been experienced that this particular phenomenon does not occur.

This point is emphasized since the preliminary evaluation of the results would indicate that, in fact, it is more efficient to work with a lower diameter and larger pressure. At present, it cannot be explained why such a conclusion is evidenced by the data, but it is obvious that such a conclusion is not valid outside of the very narrow range in nozzle diameters used in this particular test. Large quantities of concrete have been cut much more effectively at larger nozzle diameter and lower pressures where the nozzle diameter lies outside the range used in this particular program.

An additional point may be made in regard to the way in which the waterjet is cutting through the concrete. Because of the very small nozzle diameter and higher pressures the jet is restricted in the area of impact and is spalling the aggregate. This is a function, purely, of the aggregate contained in the block under test. Certain aggregates around the country cannot be cut by waterjets even at pressures as high as 60,000 psi. Under those circumstances it might be better to try to wash out the cement and leave the aggregate intact. This is not particularly difficult, and can provide a very clean cut. It may be possible to obtain such a cut operating only in the cement phase of the concrete if the waterjet pressure is held to between 10 and 15,000 psi with the relatively small nozzle dia-

meters used in this test. Under those circumstances it is possible that the waterjet would slot an adequate depth in this cement while leaving the aggregate intact, and generate a straight edge cut.